GENERAL LIBRARY
DEC 19 1919
UNIV. OF MICH.

VOLUME L NUMBER 4

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

EDITED BY

GEORGE E. HALE
Mount Wilson Observatory of the Carnegie Institution of Washington

EDWIN B. FROST
Yerkes Observatory of the University of Chicago

HENRY G. GALE
Ryerson Physical Laboratory of the University of Chicago

NOVEMBER 1919

EDWARD CHARLES PICKERING, 1846–1919 - - - - *Solon I. Bailey* 233

SOME LARGE-SCALE EXPERIMENTS IMITATING THE CRATERS OF THE MOON - *Herbert E. Ives* 245

MEASUREMENTS ON THE NEAR INFRA-RED ABSORPTION OF SOME DIATOMIC GASES *Elmer S. Imes* 251

ON PROGRESSIVE CHANGES OF THE WAVE-LENGTHS OF LINES IN STELLAR SPECTRA WITH CHANGE OF TYPE - - - - - - - - - - - *Sebastian Albrecht* 277

A PROPERTY OF THE PHOTOGRAPHIC PLATE ANALOGOUS TO THE PURKINJE EFFECT. SECOND NOTE - - - - - - - - - - - - - - - - - - - *J. A. Parkhurst* 290

ON THE DIFFUSING ACTION OF THE SUN'S GASES AS THE CAUSE OF THE APPARENTLY SHARP SOLAR BOUNDARY - - - - - - - - - - - - - - *C. G. Abbot* 295

MINOR CONTRIBUTIONS AND NOTES:

The General Illumination of the Sky, CHARLES FABRY, 308.

ERRATA - - - - - - - - - - - - - - - - - - -

November 1919 Vol. L, No. 4

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

EDITED BY

GEORGE E. HALE
Mount Wilson Observatory of the Carnegie Institution of Washington

EDWIN B. FROST
Yerkes Observatory of the University of Chicago

HENRY G. GALE
Ryerson Physical Laboratory of the University of Chicago

WITH THE COLLABORATION OF

JOSEPH S. AMES, Johns Hopkins University
ARISTARCH BELOPOLSKY, Observatoire de Poulkova
WILLIAM W. CAMPBELL, Lick Observatory
HENRY CREW, Northwestern University
CHARLES FABRY, Université de Marseille
CHARLES S. HASTINGS, Yale University
HEINRICH KAYSER, Universität Bonn
ALBERT A. MICHELSON, University of Chicago
HUGH F. NEWALL, Cambridge University
ERNEST F. NICHOLS, Yale University
ALFRED PEROT, Paris
†ANNIBALE RICCÒ, Osservatorio di Catania
CARL RUNGE, Universität Göttingen
ARTHUR SCHUSTER, The University, Manchester
FRANK SCHLESINGER, Allegheny Observatory

† Died September 24, 1919

The Astrophysical Journal is published by the University of Chicago at the University of Chicago Press, 5750 Ellis Avenue, Chicago, Illinois, during each month except February and August. ¶The subscription price is $5.00 a year; the price of single copies is 65 cents. Orders for service of less than a half-year will be charged at the single-copy rate. ¶Postage is prepaid by the publishers on all orders from the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands, Shanghai. ¶Postage is charged extra as follows: For Canada, 30 cents on annual subscriptions (total $5.30), on single copies, 3 cents (total 68 cents); for all other countries in the Postal Union, 62 cents on annual subscriptions (total $5.62), on single copies, 11 cents (total 76 cents). ¶Patrons are requested to make all remittances payable to The University of Chicago Press in postal or express money orders or bank drafts.

The following are authorized to quote the prices indicated:

For the British Empire: The Cambridge University Press, Fetter Lane, London, E.C. 4. Yearly subscriptions, including postage, 26*s.* each; single copies, including postage, 3*s.* 9*d.* each.

For Japan and Korea: The Maruzen-Kabushiki-Kaisha, 11 to 16 Nihonbashi Tori Sanchome, Tokyo, Japan. Yearly subscriptions, including postage, Yen 11.25 each; single copies, including postage, Yen 1.50 each.

For China: The Mission Book Company, 13 North Szechuen Road, Shanghai. Yearly subscriptions, $5.00; single copies, 65 cents, or their equivalents in Chinese money. Postage extra, if mailed direct outside of Shanghai, on yearly subscriptions 62 cents, on single copies 11 cents.

Claims for missing numbers should be made within the month following the regular month of publication. The publishers expect to supply missing numbers free only when losses have been sustained in transit, and when the reserve stock will permit.

Business correspondence should be addressed to The University of Chicago Press, Chicago, Illinois.

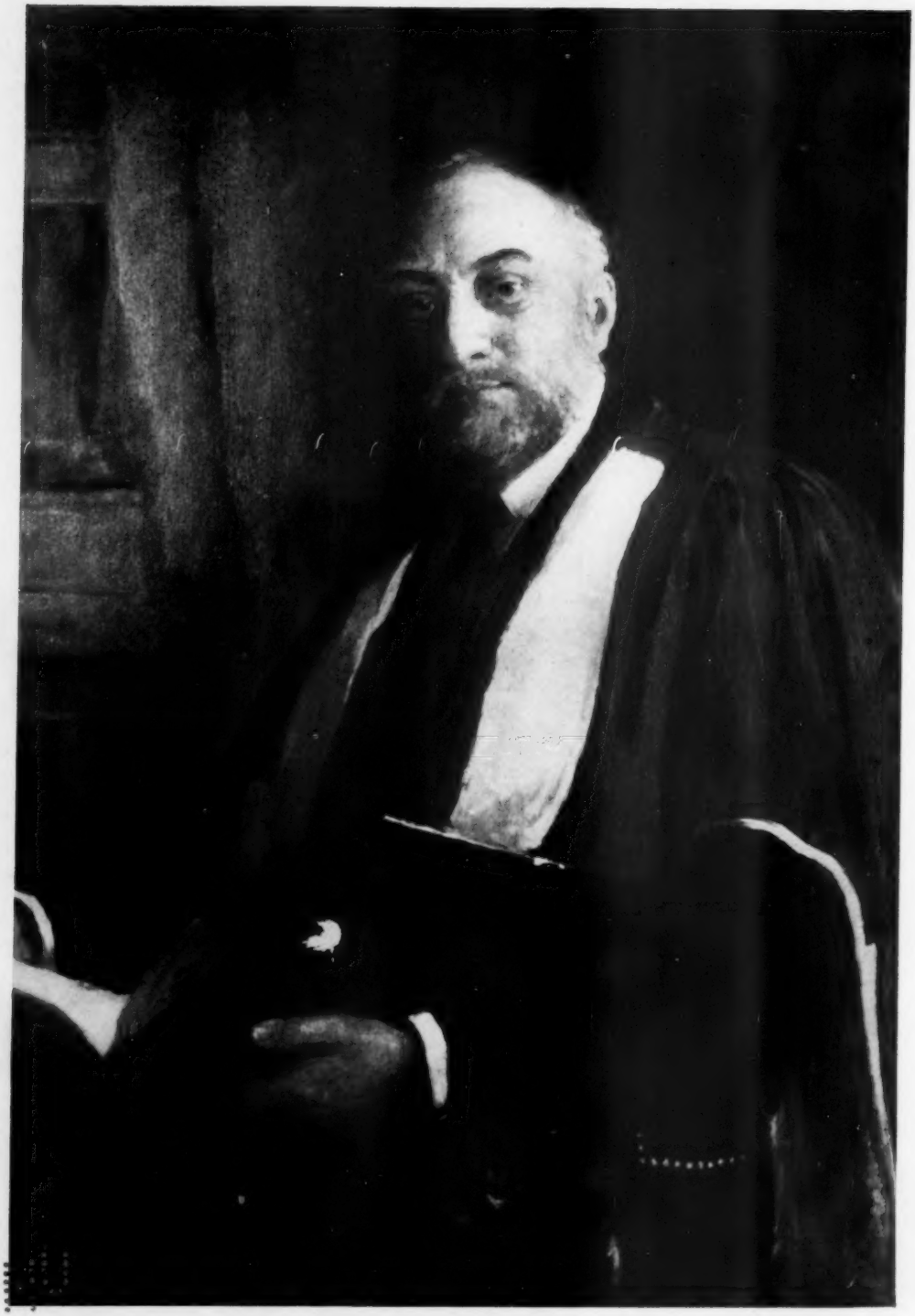
Communications for the editors and manuscripts should be addressed to the Editors of THE ASTROPHYSICAL JOURNAL, Yerkes Observatory, Williams Bay, Wisconsin.

The cable address is "University, Chicago."

The articles in this Journal are indexed in the *Readers' Guide Supplement*, New York, N.Y.

Entered as second-class matter, January 17, 1895, at the Post-office at Chicago, Ill., under the act of March 3, 1879.

Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 15, 1918.



EDWARD CHARLES PICKERING

From a painting by Miss Sarah G. Putnam, made in 1912

THE
ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME L NOVEMBER 1919 NUMBER 4

EDWARD CHARLES PICKERING, 1846–1919

By SOLON I. BAILEY

Whenever a man in any sphere of human activity accomplishes results which seem to place his name among the Immortals, the world is interested to know wherein lay his power.

Edward Charles Pickering was born on Beacon Hill, Boston, July 19, 1846. He was most fortunate in his heritage. Of an old and distinguished colonial family, he was heir to neither riches nor poverty, but to splendid opportunity which he eagerly grasped. From early boyhood to late manhood, in ill health as in good, his zeal in whatever scientific problem engaged his attention was unbounded. His education was begun in private schools. The years spent at the Boston Latin School were always regarded by him as largely wasted. He had small love of the classics and, in common with companions since more or less famous in science, he made no attempt to attain high rank in them. At the Lawrence Scientific School, however, he entered upon his work with that great enthusiasm which marked all the activities of his later life. He was graduated from this school *summa cum laude* at the age of nineteen, and was at once appointed instructor of mathematics in the same institution. Two years later he became assistant in physics at the Massachusetts Institute of Technology, and in the following year Thayer professor of physics, a position he held until called to the

directorship of the Harvard College Observatory. During these nine years forty-one scientific papers were published by him or by students under his direction, as well as two volumes of his pioneer textbook on practical physics entitled *Physical Manipulations*. He established, in connection with these volumes, the first physical laboratory in America for the use of students. The idea of such a laboratory had been suggested a few years earlier by President W. B. Rogers, of the Institute, but the details of its operation and its successful installation and management were first developed by Pickering in 1869. The great object to which his work at the Institute was directed was research. The value of the course in physical manipulation was measured to him by the success with which it taught the student to think for himself and fitted him to solve problems experimentally. Although research was his chief interest, his duties as a teacher consumed the greater part of his time. His investigations were largely concerned with light, which formed a fitting foundation for his future life-work. In later years he found that few astronomers thoroughly understood the principles involved in the various photometers which he devised for astronomical studies at the Harvard Observatory and elsewhere.

A notable contribution of a different character, however, was furnished by his early experiments with the telephone. In 1870, several years before the invention of the telephone now in common use, he devised, constructed, and tried a receiver consisting of a flexible iron diaphragm supported at the edges and replacing the armature of an electromagnet. This apparatus appears to differ in no way in principle from the receiver later employed. The possibility of protecting such a device by patent would never have been considered by him, since he held the conviction consistently throughout his life that a scientific man should place no restriction on his work which would prevent the repetition by others of any experiment of scientific interest.

Mr. Pickering also in 1876 founded and became the first president of the Appalachian Mountain Club. The great value of this club for popular purposes is undoubted, but its primary aim was scientific. Notable achievements have been accomplished in both

fields. His own chief contribution was the perfection of a light and portable micrometer level, weighing only twelve pounds, for the rapid determination of approximate positions and altitudes. To measure the positions and heights of a wide group of mountains, it was only necessary to ascend two of them and to know the horizontal positions of two and the altitude of one of the observed objects. Mr. Pickering made many thousands of observations of various points of interest in the White Mountains with this instrument. The intensity of his interests and the enthusiasm and success with which he carried out his plans made a deep impression on his associates. This is evident from the profound regard in which he is still held by the survivors among his scientific friends of those years.

Professor Pickering was chosen director of the Harvard College Observatory in 1876, at the age of thirty, and entered upon his duties February 1, 1877. The appointment of a physicist to direct an astronomical observatory caused some natural criticism from astronomers of the old school. The time was ripe, however, for the introduction of astrophysics. The beginnings had indeed been well made by Secchi, Huggins, and others, but their work constituted only a beginning which served to open the way for greater surveys and profounder details. The old astronomy of position and motion still occupied nearly all the time of the great observatories. Even the magnitudes of the stars were not fixed on any scientific basis, and the estimates of different astronomers sometimes varied by several magnitudes. In such a condition of the science the accumulation of great masses of data was necessary in various lines of investigation before any authoritative solution of most stellar problems would be possible. Of a certain great astronomer, who recently died, it was said that he put "theory first, practice in the second place." This should be exactly reversed in the case of Pickering. His plan, early arrived at, was to furnish to astronomers those facts, concerning the stars especially, which were most necessary to the progress of modern astronomy.

At first the range of his researches was sharply limited by the equipment of the observatory. There were two instruments of great power and perfection for that day, the 15-inch. equatorial

refractor and the 8-inch meridian circle. The financial resources of the observatory were insufficient to keep these actively employed and to publish the results obtained. His first care was to secure additional funds sufficiently large to accomplish this, and also to extend his researches into new fields. His *Annual Report* for 1877 contained an appeal for money, and every succeeding report included direct or indirect appeals of the same nature. He early realized that to accomplish the great schemes which he had in mind he could not depend on himself alone but must command the services of many minds and hands. This involved a great increase of endowment. Little by little this was secured, until the observatory became sufficiently strong to carry on many widely distributed investigations. His own part in this increased income was large. In all, he gave to the observatory a sum more than equal to the salary which he drew as director during forty-two years.

The first and one of the greatest of his achievements was in stellar photometry. It was necessary to bring the stars and planets into an orderly sequence, which should be on some definite and "absolute" scale. He undertook to do this for all the brighter stars in the *Harvard Photometry*. For this, however, a special apparatus must be devised, and until this was ready, and indeed throughout his life, various photometric investigations were carried on by himself and others with the 15-inch telescope. A touch of romance was lent to the beginning of these labors by the measurement, in 1877, of the newly discovered tiny satellites of Mars. Their observation taxed the 15-inch telescope to the limit of its power. Other photometric investigations with the same instrument were the observation of the eclipses of Jupiter's satellites, the determination of the relative brightness of the components of double stars, and measures of the magnitudes of Algol and other variable stars and of planets and asteroids. The accuracy of many of these observations has never been surpassed for faint celestial objects.

These results were not attained with instruments already made. In attacking these problems it was necessary to invent suitable instruments and to have them constructed and attached to the

PROFESSOR E. C. PICKERING AT THE AGE OF 45 (1891)

telescope. A long series of photometers was devised by him, depending for the most part on the principle of polarization. A Nicol prism was attached to a double-image prism so that it could turn freely around its axis. The angle was read on a graduated circle. The star to be measured was compared with another star assumed to be standard. By the revolution of the Nicol the light of the two stars was equalized, and the resulting readings gave a determination of the relative light of the two objects. Accepting the law of Pogson that the ratio of one magnitude to the next should be expressed by the quantity whose logarithm is 0.4, Mr. Pickering reduced all the stars to a system which in general left the bright stars of about the same magnitudes as given in the *Almagest*. While there was no scientific necessity for such a basis and system, the wisdom of this deference to ancient usage is amply justified. Wedge photometers were also used in various forms.

While engaged in carrying on the researches with the 15-inch telescope, the meridian photometer was constructed for the measurement of all the brighter stars. The first meridian photometer had lenses of only one and a half inches' diameter. With this he measured the brightness of 4260 stars. The results proved to be of such value that a larger instrument was constructed with which the work was extended to all stars of the magnitude 7.5, and brighter, in the northern sky. A similar work carried out below the equator made the *Harvard Photometry* complete for the whole sky and established its use almost universally.

Many years ago Mr. Pickering saw the possibilities of a photographic photometry. Many experiments were tried soon after the beginning of astronomical photography. The difficulties proved to be very great, but these were to some extent eliminated and the work is now being systematically carried forward by his former associates at the Harvard Observatory. The investigation is also being pushed at other observatories and promises to add much to our knowledge of the stars. In the last few years Mr. Pickering was much interested in photo-visual magnitudes, which may be so derived with the use of filters and isochromatic plates as to agree closely with visual magnitudes.

An appropriation from the Bache Fund in 1885 made possible the beginning of photographic investigations. These were later greatly extended by the help of the Boyden Fund and the generous gifts of Mrs. Draper. The invention of the dry plate had opened the way for swift and sure development in nearly all lines of astronomical research. Something of romance was thus lost, indeed, but the gain in efficiency was tremendous. The laborious charting of a field of stars could be done in an hour, the resulting photograph showing more stars than the eye could see with a telescope of equal size. For certain purposes the plates themselves are sufficient without reduction. Professor Pickering early grasped the idea that a large collection of such photographs, made through a series of years, would have immense value in answering questions which would constantly arise. That is, he planned to collect a history of the stars during his life, and to make this record as complete as possible. This scheme was made to cover the whole sky by a station in the Southern Hemisphere. Various kinds of photographs were undertaken, especially charts and spectra of stars obtained with the objective prism. They were made with instruments of widely different powers. As extremes may be mentioned a wide-angle ½-inch Ross-Zeiss lens covering a field of about 60° square, so that the entire sky available at any one time and place could be covered in a single night, and the 24-inch Bruce doublet. With an exposure of one hour the former of these showed stars to about the ninth magnitude, the latter to the seventeenth magnitude. The extended discoveries of novae, asteroids, variable stars, and other interesting celestial objects from this collection of photographs are ample proof of its value. A series of plates of four hours' exposure with the 24-inch Bruce was proposed and a considerable number of excellent photographs were made at Arequipa from the South Pole northward. Such a series, if it could be completed for the whole sky, would contain a hundred million stars, and from it might be derived definitive lists of clusters and nebulae for the determination of the laws of their distribution, distance, and motion. The scheme would require a long time for its completion with a single telescope, and meanwhile the "selected areas" of Kapteyn and Pickering's own "standard regions" made this complete plan less necessary.

The study of stellar spectra, carried on by several observers under Mr. Pickering's direction, constitutes one of the observatory's greatest achievements. The practical completion of the *Henry Draper Catalogue*, in which his interest was intense, even in the last days of his life, forms a fitting close to his career. To estimate its importance, one needs to consider how small was our knowledge of the nature of the stars when he began to photograph them with the objective-prism, and how intimately the Harvard classification has entered into relation with nearly all lines of astronomical research. For detailed study of bright stars and for the determination of motion in the line of sight, the objective-prism does not compete well with the slit-spectrograph, but for a *Durchmusterung* of the spectra of two hundred thousand stars no other method was possible.

Aside from the classification of the spectra, the objective-prism plates yielded enough in the way of by-products to justify Mr. Pickering's enthusiasm: several novae, hundreds of new variable stars, and long lists of peculiar stars of special interest. These results occupy much space in the *Annals*. The Harvard classification, though not final, is now universally accepted as the best available system and has received international sanction. Nothing pleased Mr. Pickering more than to know that the results obtained at the observatory were those most needed by astronomers in their investigations. Certainly no better example could be found of a recognized astronomical need than the classification of spectra to be furnished in the nine volumes of the *Henry Draper Catalogue*. The publication of this work has been awaited with unusual interest by astronomers. Indeed, in many cases it has not been awaited, since the spectra of nearly forty thousand stars have been furnished by special request in advance of publication.

During many years Professor Pickering searched for efficient means by which photographs of stars made with the objective-prism might be used for the determination of motion in the line-of-sight. Several methods were proposed. One of these was to turn the prism 180° between two exposures on the same star on a single plate. Another and perhaps more hopeful method was by the use of an absorbing medium placed in the path of the rays. Of all

the substances tried, neodymium, suggested by R. W. Wood, gives the best absorption lines for the purpose. Though not yet carried out to a successful issue, the results thus far obtained indicate that even if precise individual determinations are not possible, mean values of great importance may be hoped for where large numbers of stars are under consideration.

This conception of a vast collection of photographs of the stars, destined in time to give a history of the sky, was unique. Its execution was carried out with enthusiasm and success. To some these half-examined plates, made in many cases for the purpose only of securing as complete a record as possible, appeared unnecessary and even excited ridicule. This seems absurd now that their value has been so fully demonstrated. Hardly a nova or new variable star has been discovered for many years whose history could not in some degree be traced upon these photographs. Eros furnished an early example of their value. Discovered in 1898, its history was traced backward on the Harvard plates to the interesting opposition of 1894, thus promptly furnishing material for a precise determination of its orbit. This collection in some sense symbolizes a large part of Mr. Pickering's achievements. From it have been derived all the studies of the spectrum, all the photographic photometry, much of the work on variable stars, and discoveries in many lines. It still exists, its possibilities by no means exhausted, its value in many ways increasing as the years go by. Of course, photographic plates are not immortal, and in time their films may decay, but meanwhile they may assist in solving many problems.

One fascinating possibility still needing study on these plates is that of spectral parallaxes. The direct determination of stellar parallax is perhaps the most difficult problem in astronomy and has been impossible for the more distant stars. By the work of Adams and others it now appears that the absolute magnitude of a star can be determined from the varying intensities of the lines of certain spectral types, the relation of which to the apparent magnitude gives the distance.

Within this great collection of stellar photographs, therefore, by means of such problems as these, there still remains for Professor

Pickering the possibility of an immortality of scientific labor, more unique and worthy than ordinary fame.

It is possible that Mr. Pickering's best work was in photometric and spectroscopic lines, but he was active in many other fields. The study of variable stars has been a marked feature of the observatory under his administration. When he began his work, about 200 variable stars were known. At the time of his death 3435 variables had been discovered at the Harvard Observatory. He published in 1880 a classification of variable stars which is the accepted notation at the present time. He soon began to encourage their observation on a scale hitherto unknown. This was possible not only through the increasing resources of the observatory but also by the assistance of amateurs. This is a field wherein the amateur can make systematic observations of real value. When the American Association of Variable Star Observers was formed, he gave the members the assistance which they needed. The spirit in which this aid was given and received is well shown in the regard and affection in which he was held by the members of this Association. At their meeting in 1918 they presented him with a beautiful gift, when their president made the following reference to him: "He has assisted us in everything that we have undertaken and has carefully watched our progress along every step of the way, and the manner of his so doing has been that of the Big Brother."

The astronomy of position has not been neglected at any time in the history of the Harvard Observatory. Two zones of the *Astronomische Gesellschaft*, those from $+49°55'$ to $+55°10'$, and from $-9°50'$ to $-14°10'$, have been observed with the 8-inch meridian circle. This work has occupied the time of one professor and several assistants during the last half-century, has cost approximately $200,000, and fills a dozen volumes of the *Annals*.

When Mr. Pickering came to the observatory, only a dozen volumes of the *Annals* had been published or were ready for printing. At the time of his death nearly a hundred of these quarto volumes had been issued or were practically ready for the printer. Many of these, indeed, were chiefly the work of others, and supervised and edited by him. On the other hand, an enormous amount was his own. His interest also in the work of others

seemed as intense as in his own. His desire was to see results. If he was fond of quantity, the painstaking care with which he examined and re-examined all that he did or supervised is evidence that quantity was not sought at the expense of quality. Loyalty to his predecessors in office was one of his marked characteristics. He devoted much time and badly needed financial resources during the early years of his directorship toward completing and publishing their unfinished work.

One of the most cherished objects of Pickering's life was to secure an international fund for the benefit of astronomers of all nations. He wished to be able to assist the special man in carrying out his ideas. Such a fund would form the most fitting memorial to his name. Similar in scope was his plan for an international southern telescope, which would be devoted to the needs of astronomers everywhere.

Mr. Pickering loved to discuss but refused to dispute. He believed in the "inanity of rivalry, the pettiness of jealousy, and the joyfulness of association for the good of mankind." Over his youth and early manhood had hung that curse of New England, tuberculosis, but through all his life he worked with that tremendous enthusiasm without which, it is said, nothing great was ever accomplished. Under the liberal faith of the modern Bostonian he had a puritan conscience, which impelled him to the accomplishment of certain duties, perhaps at times against the advice of his judgment.

He caught the true spirit of the age, but was ever a little in advance of it. He had the rare gift of knowing his own powers and of making the most of himself. He did not waste time in trying the impossible. What he attempted he performed. In the surveys of the sky which he carried out he was another Herschel. Theoretical reasoning not based on well-established data had little attraction for him. He recognized that the best service he could render to astronomy was the accumulation of facts. To this end he massed all the forces he could command and instituted great pieces of research, sometimes a vast routine, that in the end a sufficient basis should be furnished for a solution of stellar problems. Not a mathematician, he was yet a master of mathematics.

His practical nature led him to adopt graphical, in place of analytical, methods, whenever nothing was thereby lost in accuracy.

Mr. Pickering loved appreciation but was not swerved from his course by its presence or absence. His persistence in what he believed was right was only equaled by the readiness with which he accepted new ideas. Until the very last of his life he had an alert, unprejudiced mind, and was ready to reject the plans of a lifetime if convinced of their error. He was prompt to give advice whenever it was asked; perhaps, in some cases, where it was not desired. Always eager for friendly criticism himself, he could not believe that anyone would wish to go on in a doubtful course when it was possible to find a better one.

He was a natural leader, but he was an indefatigable worker as well. He worked for the love of it, carrying on observations for several hours each clear night, in addition to his arduous duties as director. Of the two million observations of light concerned in the visual *Harvard Photometry*, more than half were made by him.

Mr. Pickering's patriotism was intense. His desire to assist his country in time of war was shown by several valuable suggestions to the government. He heartily condemned all practices which he regarded as contrary to civilized warfare, but retained throughout a high regard for old astronomical friends among the enemy nations.

As remarkable as were Mr. Pickering's scientific accomplishments, equally rare were his personal qualifications. For men and women he had an equal charm. His grace of manner and conversation was the constant wonder of all who knew him intimately. Over all, old and young, wise and witty or ignorant and stupid, who seemed to have any claim upon him, he threw the glamor of his personality. To astronomers especially he was ready with unlimited service. Many astronomers remember him as an ideal host. The entertainment of the American Astronomical Society in 1918 gave him special pleasure.

The following quotations from men of high scientific rank show the appreciation of his attitude: "A great, kind, unselfish man has gone." "The loss to astronomy and to science generally is inestimable, but all his friends will mourn him for his lovable personal

qualities." "His wonderful energy and enthusiasm, his alertness, his unvarying courtesy, his wide vision and generous heart, make his passing a keen personal loss even to those of us who knew him only slightly. For a number of years I have thought of him as the Dean of American Science." The memory of association with him is cherished by those who knew him intimately as one of life's choicest gifts.

Professor Pickering received nearly all the honors which the world has to bestow on a scientific man. These he valued highly as an expression of the appreciation in which his work was held.

Unknown probably to most, Mr. Pickering had strong poetic and religious elements in his nature. On his tomb he asked to have engraved the one word, "Thanatopsis." To him this word of doubtful coinage meant perhaps that view of death which after all might be a new view of life. At any rate, to his eager and always open mind, the words of Bryant appealed with special power:

> So live, that when thy summons comes to join
> The innumerable caravan, which moves
> To that mysterious realm, where each shall take
> His chamber in the silent halls of death,
> Thou go, not like the quarry-slave at night,
> Scourged to his dungeon, but, sustained and soothed
> By an unfaltering trust, approach thy grave,
> Like one who wraps the drapery of his couch
> About him, and lies down to pleasant dreams.

HARVARD COLLEGE OBSERVATORY
August 1919

PLATE IX

FIG. 1

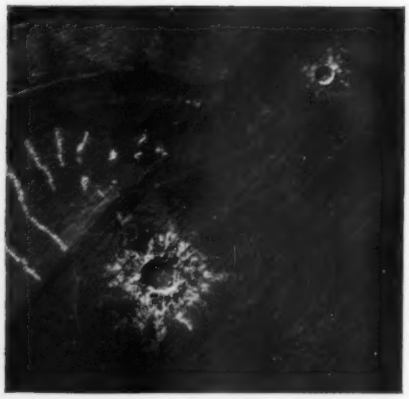


FIG. 3

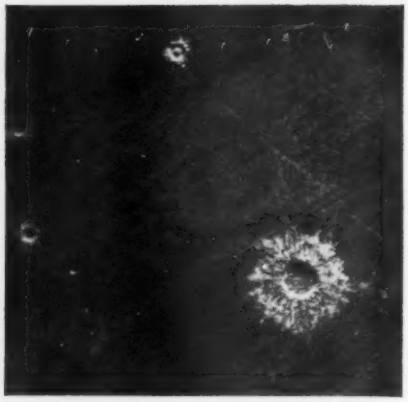


FIG. 4

FIG. 2

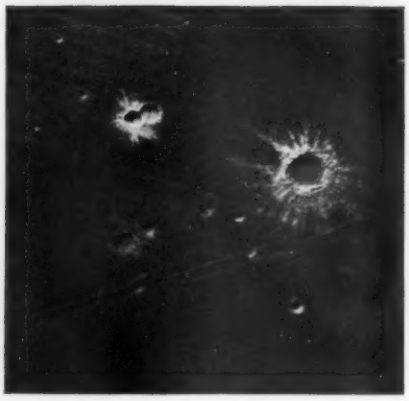


FIG. 5

a

FIG. 1.—REPRODUCED FROM W. H. PICKERING'S *The Moon*

FIG. 2.—FROM A PHOTOGRAPH OF THE MOON at 18 days, Yerkes Observatory

a, Copernicus
b, Archimedes
c, Plato
d, Theophilus and Cyrillus

SOME LARGE-SCALE EXPERIMENTS IMITATING THE CRATERS OF THE MOON

By HERBERT E. IVES

The origin of the characteristic crater-like features of the moon's surface has been the subject of frequent discussion, and a solution satisfying all who have studied the problem is far from being reached. The explanation readiest to hand, that the rings, pits, and peaks are the result of volcanic action, does not appear to be adequate when closely studied. While superficially similar in appearance to terrestrial volcanoes, the lunar "craters" exhibit significant differences of structure from these. The crater floors are lower than the surrounding country instead of higher, as they are in most terrestrial volcanoes, the central peak is often missing, and the amount of material piled up in the ring mountain is less than would be deposited there by the volcanoes we know. It has, however, been pointed out by W. H. Pickering that the volcanoes of Hawaii are quite similar to the lunar configurations.

Opposed to the volcanic theory is the meteoric or impact hypothesis. This assumes that the lunar craters are the result of the impact of meteors. Objections that have been raised to this theory are the almost uniformly circular shape of the craters, which offer difficulty on the ground that many meteors would strike at a glancing angle, the elevated central peak, and the enormous number of the impacts represented, while the earth has apparently been immune. Reference will be made more in detail to these and other objections in the discussion of the subject-matter of this paper, which supports the meteoric as opposed to the volcanic hypothesis. Excellent reviews of the theories of the cause of the moon's surface structure will be found in W. H. Pickering's *The Moon* and in Moulton's *Introduction to Astronomy*.

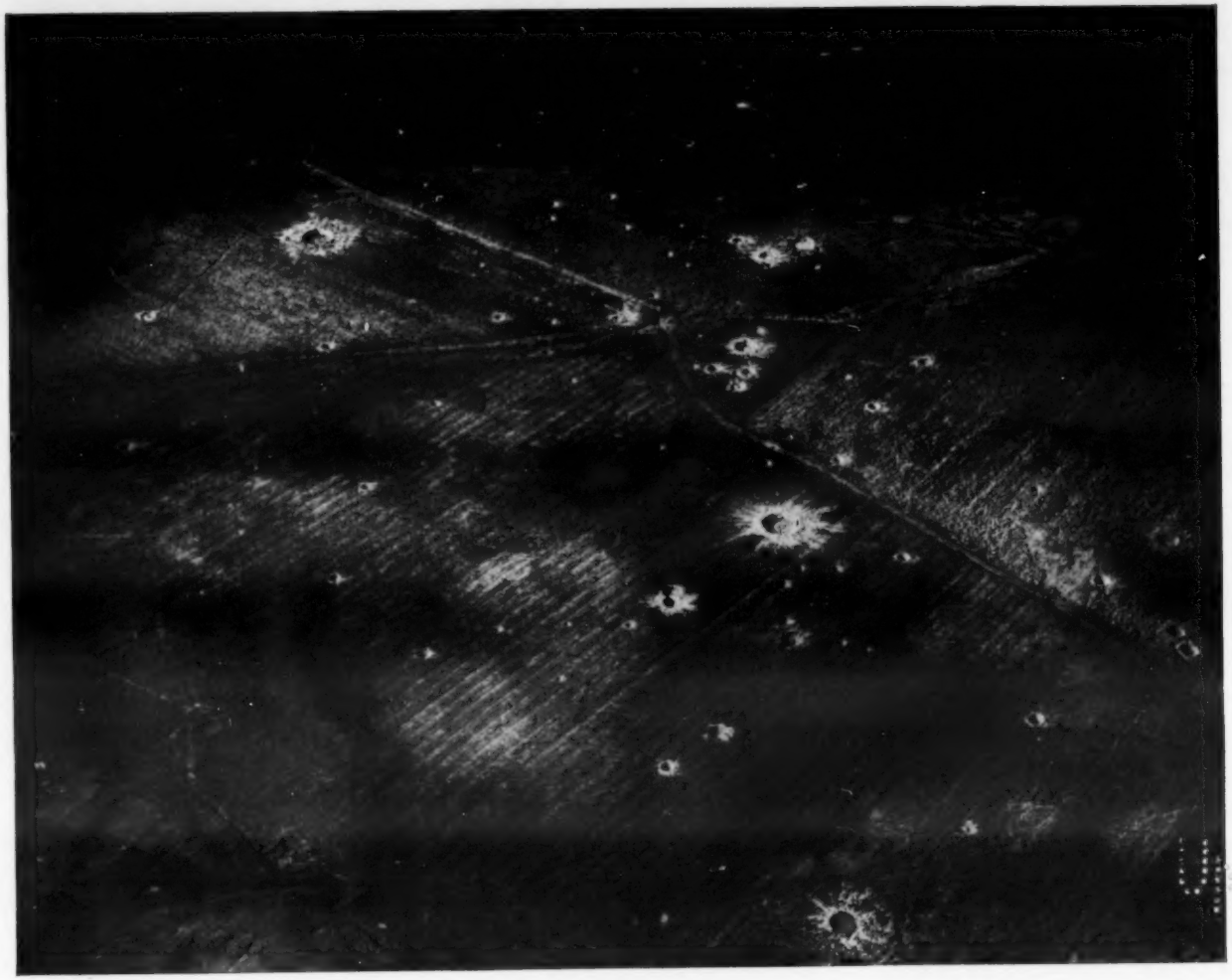
Reference to Plate IX (Figs. 1 and 2) will bring to mind the characteristic features of the moon's surface. Copernicus, the large crater in the upper part of Fig. 1, exhibits the circular ring, the level

floor, and the central small elevations or peaks, all characteristic details of the typical lunar crater. The radiating streaks or "rays" are visible in the photograph, though not shown as well as under some other conditions of lighting, and are never so extensive as the rays from Tycho, which extend over a large portion of the Southern Hemisphere. To the left and below Copernicus are smaller characteristic craters, both with and without the central peak. To the left are the large ringed plains Archimedes and Plato, which have no central peaks at all, and whose floors are practically flat. All gradations between the extremes represented by the small craters with sharp central cones and the ringed plains are to be found. Figure 2 is inserted chiefly to show one of the most striking instances of overlapping craters, Theophilus and Cyrillus, a phenomenon which must be readily covered by any suggested explanation of the lunar configurations.

Various attempts have been made in the past to duplicate the craters of the moon by laboratory experiment. Some of these are reproduced in W. H. Pickering's *The Moon*. Reference may be made to that work for detailed explanation and discussion of these experiments, which show "impact" craters, made by shooting clay pellets at a clay surface, and other pictures of effects obtained in cooling slag and paraffin, and therefore belong more properly to the "volcanic" theories. A point of considerable importance, shown in his first picture (his Plate A), and also found in experiments made by shooting lead bullets at a lead surface, is the occurrence of the central elevation or peak, formed apparently by a species of rebound. This answers one of the earlier objections which appeared rather difficult to meet on the meteoric theory.

All these laboratory experiments are on a very small scale, compared with the ten, twenty, or even fifty miles which represent the diameters of many lunar craters. The present paper describes some experiments on a scale which, while still small compared with the size of the feature it is desired to duplicate, is nevertheless enormously greater than the laboratory scale of those mentioned above. The experiments were not made with any reference to lunar theories but were incidental to the development of munitions

PLATE X



PHOTOGRAPH FROM AIRPLANE OF CRATERS MADE BY BOMBS DROPPED FROM AIRPLANES AT LANGLEY FIELD

of war. They are therefore a scientific by-product of the Great War. Specifically the craters which are illustrated and discussed below are bomb craters made by the explosion of experimental bombs, dropped from airplanes at Langley Field, Virginia. A photograph of the bombing target and a number of craters is shown in Plate X. The resemblance to the pitted surface of the moon will strike the most casual observer.

With special reference to the scale of the experiments, we mention that twenty men with joined hands just span one of the craters. This particular crater was caused by the explosion of several hundred pounds of T.N.T. Also in connection with the scale on which the experiments were performed belongs a description of the observing platform. Obviously craters of this size would not be easily photographed from any position on the ground; the laboratory bench used was in fact an airplane, and Figs. 3, 4, 5, and Plate X are aerial photographs.

Attention may be called in some detail to the points of resemblance between these bomb craters and the lunar configurations. Figure 3 shows two types of crater. The smaller one, in the upper right-hand corner, exhibits all the features of a lunar crater of medium size. It has the circular surrounding wall, the central peak, and a few short radiating streaks. The larger crater resembles more nearly the ringed plains. Its floor is flat, due to the seeping in of water. This of course would not happen on the moon, with its present waterless condition, but there is no objection to the suggestion that the larger ringed plains of the moon date from a period when water, carrying sediment, could have leveled off the floor of the craters in just this way.

Figure 4 shows, in addition to a large and a small crater of types already discussed, a very striking example, in the small crater at the top, of the production of a central peak. This peak is indeed much more pronounced than any on the moon, probably due to the earth in which the bomb fell being damp and softer than the materials of the moon. It is at any rate a most conclusive demonstration of the ability of a body (of the proper sort) striking a surface to produce an elevation.

Figure 5 shows, in the largest crater, a formation greatly resembling Copernicus, in its central peaks, circular wall, and radiating streaks. The resemblance, it may be remarked, was still more striking a few weeks before these pictures were taken, before the collection of water in the cavity. To the left in the same figure will be seen a pair of overlapping craters, similar to Theophilus and Cyrillus, easily explainable on an impact theory, but harder as a result of volcanic action. The smaller pits near "Copernicus" are practically identical in appearance to those near the real Copernicus.

These few words of description are sufficient, since the photographs largely speak for themselves. It is believed to be evident that they show very striking similarity between the craters produced by the explosion of bombs and the craters of the moon. What then is the significance of this similarity of appearance?

It may at first thought seem far-fetched to liken meteors to explosive bombs, which is the most direct application that can be made of these experimental results. But on further study this interpretation, far from being an obstacle to considering the experiments as pertinent, rather adds to their significance. It may first of all be pointed out that meteors striking the earth's atmosphere not only flash into incandescence, but do frequently burst with terrifying reports, spreading their fragments over a considerable territory. Most light on this point is furnished by some simple calculations, as follows: The velocity of meteors striking the earth's atmosphere varies between 16 and 64 km per second. Let us take a meteor traveling with the lower of these speeds, and assume that it strikes, not the earth's atmosphere, through which its velocity is slowly dissipated, but the surface of the moon, at which it would arrive with its full velocity. Calling the mass of the meteor m, its velocity v, its specific heat s, and the mechanical equivalent of heat J, we have the following equation for the temperature to which the meteor will be raised, assuming all the generated heat to remain in the meteor itself:

$$\tfrac{1}{2}\, mv^2 = ms(T-T_0)J,$$

where T_0 is its original temperature and T is the temperature to which it is raised. Putting in the above velocity, the value for J (41.8×10^6), assuming 0.2 for s, and zero for T_0, this equation gives for T the figure 150,000 degrees Centigrade! Even if we assume that nine-tenths of this heat is given up to the surroundings, we still have in the 15,000° C. a temperature amply sufficient to gasefy any known material, that is, *to produce an explosion.*

Thus our calculation leads to the conclusion that a meteor striking the moon, with even the lowest velocity at which these are observed, would become a very efficient bomb, and should therefore produce the kind of crater we can imitate on the earth only by filling our slowly moving military aerial bombs with explosive material. And not only does this explanation take care of the general appearance of the craters, but it affords an answer to the perplexing question presented by the almost uniformly circular shape of the lunar craters; for it is clear that the shape of the cavity has no reference to the angle at which the bomb strikes, but takes its form from the symmetrical explosive forces. Moreover, the available energy is so great that even if the meteor strikes at very great angles to the vertical the result will be an explosion. It has, however, been shown by G. K. Gilbert that the vast majority of meteors would strike at angles within 30° of the vertical.

Some of the objections which have been raised to the meteoric theory may be touched on in conclusion, considered more especially in reference to the suggestions of this paper. One is that the heat generated by the impact of the meteor would be so great as to melt the crater walls. Obviously this criticism errs only in not going far enough into the matter and finding that the generation of heat is so much beyond that necessary for the melting of rock as to put an entirely new face on the problem, leading, as we have seen, to the conception of the meteor as an explosive bomb. A second objection is that the earth should show similar effects of bombardment. We may note in passing that the Cañon Diablo, the most perfect imitation we have of a lunar crater, bears numerous evidences of having been caused by an explosion of other than subterranean origin. But the

most complete answer to this criticism is found by noting, first, that the earth is surrounded by an atmosphere which in previous ages must have been much denser than now and so would dissipate the energy of falling meteors, as indeed we see it doing now; and second, that the earth's surface has been undergoing the processes of upheaval and weathering for perhaps countless ages since the collision with the giant meteor swarms which permanently marked the dead and atmosphereless lunar surface.

PHILADELPHIA
June 1919

MEASUREMENTS ON THE NEAR INFRA-RED ABSORPTION OF SOME DIATOMIC GASES

By ELMER S. IMES

The importance of the study of the near infra-red absorption bands of gases is being more clearly realized the farther this study is carried. This importance arises from two main considerations. The first is the information which the absorption in this region gives with regard to the structure and mechanics of the molecule. This includes, of course, the inferences as to atomic structure, which are not only possible, but become necessary if the molecular facts are to be explained. The second is that there is found here a new application and test for the quantum theory in that it is extended to the originally excluded region of the rotational energy of molecules.

SUMMARY OF THEORY AND PREVIOUS WORK

It was Drude[1] who first announced the theory that the infra-red absorption and emission bands of the majority of substances have their origin in the vibrations of electrically charged atoms and molecules, and not in the oscillations of the electrons within the atoms. The two widely separated absorption regions usually appearing in the infra-red spectra of gases were naturally assigned, the one in the far infra-red to molecular rotation and that in the near infra-red to atomic vibrations within the molecule. N. Bjerrum[2] pointed out, however, that in all probability the shorter-wave absorption was due to a combination of the two frequencies, that of rotation and that of vibration. This observation was based on Lord Rayleigh's[3] combination principle: viz., that an oscillator which emits and absorbs at a frequency ν_0 due to its oscillations alone would, when rotating about an axis perpendicular to its line of vibration with a frequency ν_r, emit and

[1] *Annalen der Physik* (4), 14, 677, 1904.

[2] *Nernst Festschrift*, p. 90, 1912.

[3] *Philosophical Magazine* (5), 24, 410, 1892.

absorb at the new frequencies $\nu_0+\nu_r$ and $\nu_0-\nu_r$. The assumption of a Maxwellian distribution of rotational velocities would require that the near infra-red band consist of two broad absorption areas having maxima at $\nu_0 \pm \bar{\nu}_r$, where $\bar{\nu}_r$ is the most probable rotational frequency, and a sharp maximum for ν_0 due to molecules whose rotation frequency was zero or in a plane perpendicular to the line of sight. W. Burmeister's[1] work in this region showed the two broad areas for most of the gases investigated, but gave no sign of the sharp line corresponding to ν_0, from which it was concluded that either the dispersion used was not great enough to show it, or, at least in the case of diatomic molecules, there might be no absorption for ν_0, i.e., no molecules having no rotation.

H. Rubens and H. von Wartenberg[2] had found in the far infra-red the bands for some of the gases investigated by Burmeister, and the values for $\bar{\nu}_r$ computed from Burmeister's doublet maxima agreed well with their directly obtained values.

A complication arose, however, in the discovery that these near infra-red absorption bands did not always present, even with the low dispersion available, continuous areas with a single maximum each for $\nu_0+\nu_r$ and $\nu_0-\nu_r$. Rubens'[3] work on the water-vapor band at 6 μ and even F. Paschen's[4] much earlier work on the same band showed many separate maxima in these areas. Finally Eva von Bahr[5] in her work on water-vapor and hydrochloric acid showed such marked discontinuity in these bands that an extension[6] of the theory of their origin, abandoning the assumption of a Maxwellian distribution of rotational velocities and introducing the quantum theory, was made necessary. As a matter of fact W. Nernst[7] had previous to this time arrived at the conclusion that the quantum theory must be applied to molecular rotation. This

[1] *Verhandlungen der deutschen physikalischen Gesellschaft*, **15**, 589, 1913.

[2] *Ibid.*, **13**, 796, 1911.

[3] *Sitzungsberichte Preussische Akademie*, p. 513, 1913.

[4] *Wiedemanns Annalen*, **52**, 215, 1894.

[5] *Verhandlungen der deutschen physikalischen Gesellschaft*, **15**, 710, 731, 1150, 1913.

[6] N. Bjerrum, *loc. cit.;* E. von Bahr, *loc. cit.;* A. Eucken, *Verhandlungen der deutschen physikalischen Gesellschaft*, **15**, 1159, 1913.

[7] *Zeitschrift für Elektrochemie*, **17**, 265, 1911.

conclusion was based on two observations: first, that molecular rotation causes radiation in the case of charged molecules; and, second, that even for infinitely thick layers of gas no shorter wave-lengths are emitted. Work was done on the specific heat of gases at low temperatures with a view to finding this quantum effect, and various explanations of the results arrived at were attempted. Perhaps the best of these was that of P. Ehrenfest[1] who proposed the equation

$$\tfrac{1}{2}I(2\pi\nu_r)^2 = n\frac{h\nu_r}{2},$$

(where I is the moment of inertia of the molecule, ν_r the rotation frequency, n a whole number, and h Planck's constant), as representing the energy of rotation of a diatomic molecule and as a starting-point in the desired explanation. This equation differs from that proposed by Bjerrum[2] by the factor 2 in the denominator of the second member of the equation, since Ehrenfest concluded that the rotation quantum of energy is $h\nu_r/2$ instead of $h\nu_r$ as assumed by Bjerrum. E. C. Kemble[3] gives a derivation, based on the classical statistical mechanics, which leads to the equation

$$I = \frac{RT}{4\pi^2\bar{\nu}_r^2 N}$$

as giving the moment of inertia of a diatomic molecule in terms of the rotation frequency, $\bar{\nu}_r$, obtained from the Bjerrum doublet. He shows that this checks with Ehrenfest's assumption rather than with that of Bjerrum.

It is unfortunate that only the order of magnitude of numerical results computed from such formulae is possible of verification. This, however, in no sense minimizes the importance or the desirability of further and more exact work on the infra-red absorption of diatomic gases. There can be little hope of interpreting properly the results already obtained in the cases of water-vapor and CO_2, to say nothing of more complex molecules yet to be studied, until by

[1] *Verhandlungen der deutschen physikalischen Gesellschaft*, **15**, 451, 1913.

[2] *Loc. cit.*

[3] *Physical Review* (2), **8**, 689, 1916.

systematic study of these simpler diatomic molecules the material for generalization is gathered.

In the hope of adding to the amount of such material available for theoretical work the writer undertook the study of the absorption of HCl in the near infra-red, with greater dispersion than had previously been available. Burmeister's[1] original curve for this gas showed only the doublet consisting of broad areas having maxima at 3.4 μ and 3.55 μ. Von Bahr[2] succeeded in resolving these into twelve separate maxima, of which five were on the long-wave side of the center, thus making only five pairs available for measurement. Finally J. B. Brinsmade and E. C. Kemble[3] have published, since this work was begun, a curve for HCl showing eight maxima on the long-wave side of the center of the band at 3.46 μ, as well as a partially resolved curve for the "harmonic" at 1.76 μ.

It has been possible in the present work to extend both of these, there being twelve pairs of maxima given for the band at 3.46 μ and the band at 1.76 μ being resolved over eight pairs of maxima. In addition to these curves for HCl the writer has also obtained curves for the HBr band at 3.91 μ and the HF band at 2.52 μ. For the former of these Burmeister has published a doublet having maxima at 3.84 μ and 4.01 μ. For the latter the writer has found no published work.

APPARATUS

The apparatus designed and used by W. W. Sleator[4] in his work on water-vapor was admirably adapted to this present work and was fortunately available.

The galvanometer.—The galvanometer is of the Paschen type, a modification of the Thomson four-coil astatic instrument, and was built in the department's shop. The resistance of this galvanometer as used in the present work is approximately 2 ohms and

[1] *Loc. cit.*

[2] *Philosophical Magazine* (6), **28**, 71, 1914; *Verhandlungen der deutschen physikalischen Gesellschaft*, **15**, 1150, 1913.

[3] *Proceedings of National Academy of Sciences*, **3**, 420, 1917.

[4] *Astrophysical Journal*, **48**, 125, 1918.

with the scale 200 cm distant and the period adjusted to 6 seconds the sensitivity is about 2.2×10^{-10} amp. per mm deflection.

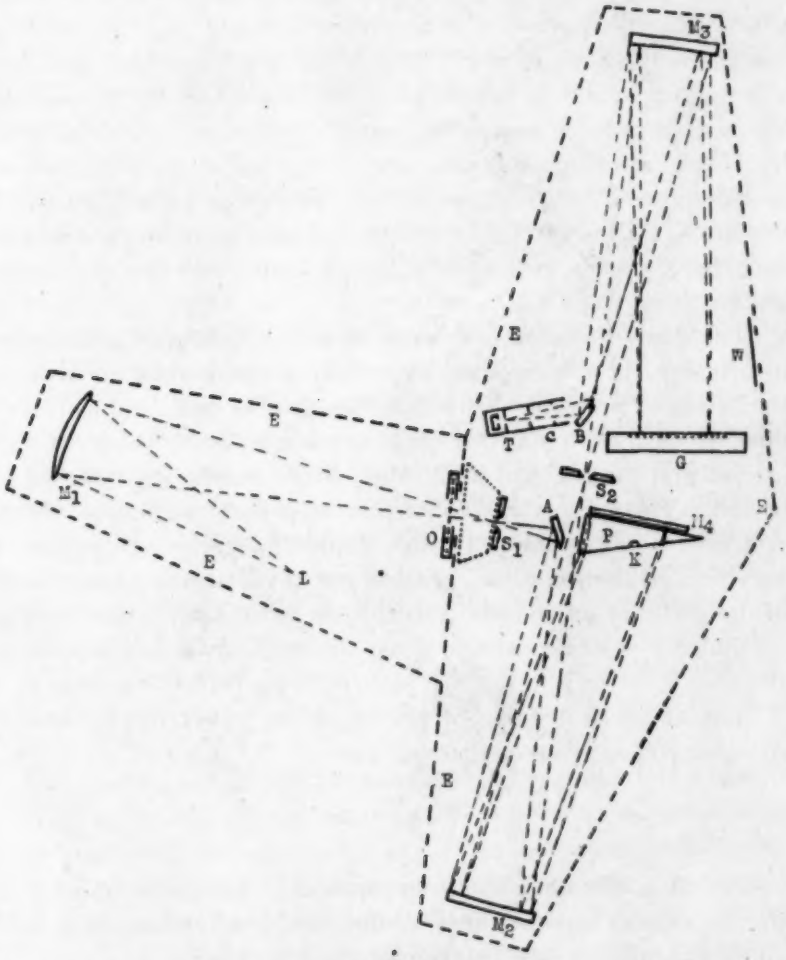


FIG. 1.—The spectrometer

L, Nernst glower; S_1, S_2, slits; M_1, 10 cm mirror, f = 20 cm; *P*, salt prism; M_2, M_3, 10 cm mirrors, f = 50 cm; M_4, *A*, *B*, plane mirrors; *G*, grating; *C*, case for *T*, the thermopile; *W*, window in box *E*; *O*, shutter. The path of the light is $LM_1S_1AM_2PM_4PM_2S_2M_3GM_3BT$. A spectrum appears at S_2. *P* and M_4 rotate together about *K*, so that any region of the spectrum may be isolated for the grating, and the overlapping of spectra is avoided. (From paper by W. W. Sleator, *Astrophysical Journal*, **48**, 127, 1918.)

The spectrometer.—Figure 1 shows the arrangement of the spectrometer, which consists really of two spectrometers, both of the mirror type. The first is a prism spectrometer, $S_1AM_2PM_4M_2$, which presents a portion of its spectrum to the slit, S_2, of the grating spectrometer, $S_2M_3GM_3BT$. The prism is of rock salt and has a refracting angle of about 18°. Its face is about 12×14 cm. Three gratings were used in the course of the work—a brass grating by Hilger, a 7500-line grating, and a 20,000-line grating, both on speculum metal by Anderson, of Johns Hopkins University. With the brass grating the spectrometer constant is 211,476 A, while with the 7500-line grating it is 67,693 A and with the 20,000-line grating it is 25,375 A.

The double-spectrometer method has proved highly successful in bringing the desired high dispersion of the grating to bear on the infra-red problem. Obviously the grating must not be called upon to analyze a spectral range containing wave-lengths which are integral multiples of each other, if the results are to be interpreted. This is especially true where, as in the present case, photographs are impossible. In the double-spectrometer method a very limited portion of the prism spectrum is thrown upon the slit of the grating spectrometer. If this slit is narrow enough to allow no multiple wave-lengths to pass, the problem of overlapping is solved.

The theoretical value of the resolving power of the grating spectrometer is given in the equation

$$d\lambda/\lambda = 1/Nn$$

(where $d\lambda$ is the wave-length separation of two lines which may just be seen as separate lines, N the number of grating lines used, and n the order of the spectrum observed).

For the 7500-line grating at the center of the HCl band at $3.46\,\mu$, the beam covering 7.5 cm of grating surface and the observations being taken in the first-order spectrum, this equation gives

$$d\lambda = \frac{3.46}{22500\times1} = 0.00016\,\mu = 1.6\text{ A}.$$

But this is based upon the assumption of infinitely narrow slits, which is not at all the case in this work, both slits of the grating spectrometer being 0.5 mm wide. A better idea of the resolution obtained may be gained from the following consideration. The width of the thermopile slit corresponds to 1.7 minutes' angular displacement of the grating. This is $d\theta$ in the equation

$$d\lambda = k \cos \theta d\theta$$

derived from the spectrometer equation $\lambda = k \sin \theta$. Substituting this value of $d\theta$ and that of $\cos \theta$ for $\lambda = 3.46\ \mu$, it is found that

$$d\lambda = 29.1 \text{ A.}$$

In other words the thermopile slit includes 29 A of the spectrum formed by this grating at 3.46 μ. Kemble worked with approximately 70 A and von Bahr with 100 A for their best results.

The thermopile.—The "eyepiece" of the spectrometer consists of a thermopile and the galvanometer. The thermopile is a linear bismuth-silver group made by Coblentz. It has ten junctions in its center line and a resistance of about 2 ohms. It is mounted behind a 0.5 mm slit at the focus of the mirror M_3, the beam from M_3 being reflected by the plane mirror B at about 90°, so that the thermopile will not obstruct the beam from the slit S_2 to M_3. The mounting is so designed as to keep the thermal junctions at the same temperature, except when radiation is absorbed by the row exposed to the slit.

The source.—A Nernst glower was used as the source of energy. The work was started with the Nernst lamp in practically its original form and driven by D.C. from a storage battery for the sake of steadiness. Toward the end of the work, however, the original mounting of the filament had given out and it was impossible to obtain new parts for its repair. Accordingly the expedient of simply mounting the filament in a suitable alundum cement mold and using a bank of tungsten lamps as ballast was resorted to. In order to avoid a troublesome amount of polarization of the filaments A.C. was used at this stage. As all of the observations were taken between 1:00 A.M. and 5:00 A.M., when the mechanical and magnetic disturbances to which the galvanometer responds

so decidedly were at a minimum, the fluctuations of voltage on the A.C. lines were practically negligible. Furthermore, current was drawn almost directly from a transformer on the 2300-volt lines, having no other load, and the glower circuit was so arranged that the fall of potential across the filament was only a fraction of the total fall in the circuit, thus making steadiness quite assured.

The absorption chamber.—The absorption chamber was of brass, 15 cm long and about 8 cm in diameter. For the greater part of the work thin mica plates were used as windows. They were cemented over the ends of the chamber, and another pair of plates, cut from the same sheets, was so mounted as to be in the beam when the chamber was out. The thickness of these plates was of the order of 0.03 mm. For work in the region of 2.5 μ and at shorter wave-lengths certain specimens of glass plates were available as windows..

Although the total length of the air path of the beam of light is more than 5 meters, the greater part of it is inside the box that contains the spectrometer, and is dried by vessels of calcium chloride, while the length of the absorption chamber is quite 20 per cent of that of the undried air path outside the box. Accordingly, for the part of the work done in regions of strong water-vapor absorption—notably at 2.6 μ—it was thought best to provide a compensating chamber similar in dimensions to the absorption chamber and carefully filled with dried air that had also been freed from CO_2 by passing through KOH solution.

METHODS AND RESULTS

Hydrochloric acid.—The first work was done with HCl in the region of 3.5 μ. The gas was generated by dropping H_2SO_4 on $CaCl_2$ and dried by being passed through concentrated H_2SO_4. Both chemicals were the "analyzed" product of the Baker and Adamson Company. A slow stream of the gas was kept passing through the absorption chamber and disposed of by absorption in water. Gum rubber tubing was used, since the ordinary vulcanized tubing was attacked by the HCl giving rise to enough H_2S to be distinctly perceptible by its odor. The unequivocal nature of the curves obtained is taken as sufficient evidence of the

purity of the HCl thus generated, so far as the presence of any substances having overlapping absorption is concerned.

For each point of the curve—one minute of arc apart—six to eight readings of the galvanometer deflection were taken through the absorbing gas and a like number through only the compensating plates, the deflections being obtained by opening or closing the shutter in front of the slit S_1. These readings were not taken consecutively, but alternately in pairs—two with the chamber "in," then two with it "out," and so on. The percentage of absorption was computed from the two averages, the direct ratio between the "in" and "out" averages being translated into a per cent transmission, and the difference between this and 100 per cent being the per cent absorption plotted against the grating setting for that point of the curve. This method has obvious advantages over a method used by some observers who have gone over the entire band first with no absorbing medium (sometimes vacuum) in the chamber, and then with the chamber filled with the substance under observation. Any failure to reproduce a spectrometer setting must result in a corresponding error in the value so obtained. This error would be especially large in the case of a substance having, for example, the very sharp absorption maxima shown by HBr (Fig. 6).

The extreme sensitivity of the galvanometer used in this work to the slightest mechanical or magnetic disturbance is a source of regret. Many times it was not possible to obtain consistent deflections even during the favorable hours, between midnight and dawn, chosen for observation. No claim for extreme accuracy is made for the percentages obtained, but it is not likely that there is any uncertainty with regard to the location of the maxima, which have all been repeated—some as many as four or five times and never with a greater disagreement than two or three angstroms. The location of these maxima, and not their magnitude, has been the problem.

Figures 2 and 3 give the curves obtained for the HCl band at 3.46 μ with two different gratings. Table II gives the measurements and computations made from the better curve. Figure 5 gives the curve obtained for the so-called harmonic of HCl at

1.76 μ with the 20,000-line grating and Table III gives the measurements and computations from this curve.

These curves as well as those for HBr and HF (Figs. 6 and 7) have been idealized to the extent of omitting small irregularities

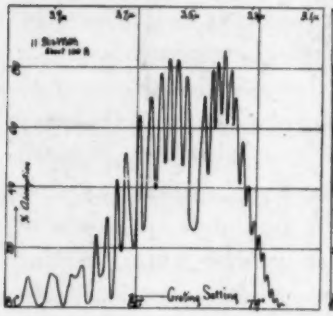


FIG. 2.—The HCl band at 3.46 μ, mapped with brass grating.

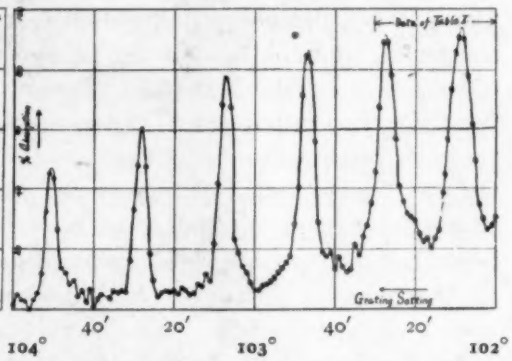


FIG. 4.—A portion of the HCl band at 3.46 μ, plotted from a single set of data.

The curves given in Figs. 2, 3, 5, 6, and 7 are plotted from averages of such sets of data and have omitted the slight irregularities appearing in the minima above, since they are not significant.

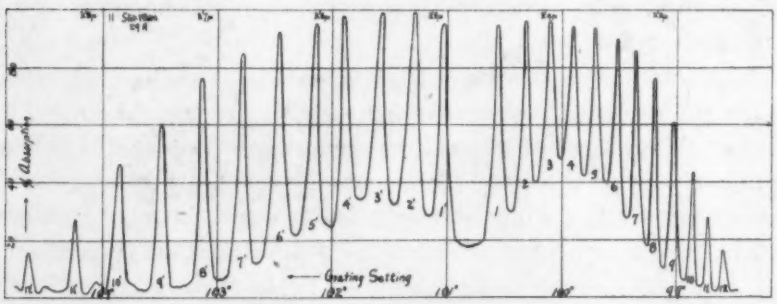


FIG. 3.—The HCl band at 3.46 μ, mapped with 7500-line grating. HCl at atmospheric pressure.

and averaging all the percentages obtained for each point. Table I gives specimen data and Fig. 4 shows the actual curve plotted from this data for a small portion of the HCl band at 3.46 μ.

Hydrobromic acid.—HBr was obtained in a satisfactorily pure state by the direct union of hydrogen and bromine. The hydrogen

was obtained by the electrolysis of NaOH solution and was carefully dried. Chemically pure bromine was washed in a KOH solution and twice distilled at as low a temperature as possible. The hydrogen was then bubbled through the bromine and the mixture passed through a combustion tube in which there was a platinum coil heated to a bright red by an electric current. The product was delivered through a long vertical glass tube surrounded by a mixture of snow and calcium chloride to condense any uncombined bromine as well as any remaining traces of water-vapor. Burmeister[1] speaks of drying HBr by passing it over P_2O_5. This process would give rise to volatile compounds of phosphorus and bromine, and would no doubt account for some of the difficulty he had in obtaining satisfactorily pure HBr.

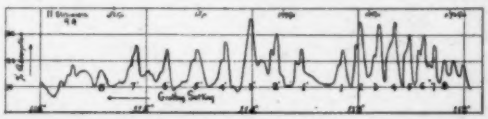


FIG. 5.—The HCl band at 1.76 μ, mapped with 20,000-line grating. HCl at atmospheric pressure.

Because of the rather elaborate nature of the apparatus required for the generation of HBr no attempt was made to keep a stream of the gas passing through the absorption chamber. It was thought sufficient to start each new series of observations with a freshly generated supply, the chamber having been washed out by drawing dry air through it by means of an aspirator for half an hour before it was filled with the gas. It was difficult to determine when the pressure of the gas in the chamber was that of the atmosphere; i.e., when all the air was displaced. Furthermore, it was aimed to generate the HBr so that an excess of hydrogen would be present and no simple means of determining constancy in the amount of this excess was at hand. The result is that the relative intensities of the various absorption maxima in the curve obtained for HBr cannot be taken as significant unless they were obtained in the same series of observations. This is not important, as

[1] *Verhandlungen der deutschen physikalischen Gesellschaft*, **15**, 596, 1913.

TABLE I

Typical Data

HCl Band, 7500-line grating, June 18, 1917, 12:45 A.M.
Glower current = 0.75 amp.
Galvanometer period = 7 sec.
Grating temperature = 20°.5 C. Grating zero = 70°0′0″

Circle	In	Average	Out	Average	Percentage Trans.	Percentage Abs.
102°0′	7.5–7.4–7.8–7.7–7.6–7.5	7.6	11.5–11–10.5–10.8–10.9–11	10.95	69.4	30.6
1′	7.4–7.8–7.7–8.0–8.0–7.6	7.75	10.5–10.7–10.8–10.7–10.9–10.7	10.7	72.3	27.7
2′	8.0–7.8–8.0–7.9–8.0–7.8	7.9	10.5–10.7–11–10.5–10.8–10.7	10.7	73.7	26.3
3′	7.0–7.4–7.6–7.5–7.4–7.4	7.4	10.6–10.4–11–10.6–10.5–10.6	10.6	69.8	30.2
4′	7.0–6.5–6.9–6.9–7.0–7.0	6.9	10.5–10.8–10.5–10.6–10.4–10.5	10.55	65.4	34.6
5′	5.0–5.5–5.0–5.5–5.3–5.5	5.3	10.3–10.2–10.5–10.6–10.3–10.5	10.4	50.9	49.1
6′	4.0–4.0–4.2–4.0–4.1–4.0	4.05	10.5–11–10.2–10.9–10.6–10.9	10.65	38.0	62.0
7′	2.5–2.4–2.0–2.4–2.3–2.3	2.3	10.4–10.5–10.4–10.4–10.5–10.5	10.45	22.1	77.9
8′	About 1.0	1.0(?)	10.6–10.5–10.7–10.7–10.6–10.5	10.6	9.4	90.6(?)
9′	About 1.0	1.0(?)	10.3–10.3–10.8–10.2–10.3–10.5	10.4	9.6	90.4(?)
10′	1.5–1.5–1.4–1.4–1.5–1.4	1.45	10–11–9.6–10.5–10.2–10.1	10.2	14.2	85.8
11′	2.8–2.5–2.8–2.7–3.0–2.7	2.75	10.3–10.7–10.4–10.5–10.6–10.4	10.5	26.2	73.8
12′	4.8–4.5–4.7–4.6–4.6–4.7	4.65	10.8–11.2–10.2–10.8–10.7–10.8	10.75	43.2	56.8
13′	7.0–6.5–6.0–6.5–6.0–7.0	6.5	10.5–10.5–11–10.5–10.7–10.5	10.6	61.3	38.7
14′	7.0–7.5–7.0–7.5–7.0–7.5	7.25	10.0–11–10.5–10.4–10.5–10.5	10.5	69.0	31.0
15′	7.8–7.9–7.5–8.5–8.0–8.0	7.95	10.2–10.8–10–10.7–10.3–10.5	10.4	76.4	23.6
16′*	11.5–11.2–11.7–11.4–11.5–11.4	11.45	14.2–15–15–14–14.5–14.6	14.55	79.2	20.8
17′	11–11–11–10.7–11–10.8	10.9	14–14.5–14–14.2–14.1–14.3	14.2	76.7	23.3
18′	11–10.5–11.5–11–11	11.0	14–14.2–14–14.7–14–14.3	14.2	77.5	22.5
19′	11–10.5–11–11–11–10.9	10.9	14.7–14–15–14.2–14–15	14.5	75.2	24.8
20′	10.5–10.5–10.5–10.2–10.3–10.5	10.4	14.6–14.8–14.7–14.9–14.7–14.8	14.75	70.5	29.5
21′	10–10–10–10.5–10–10	10.1	14.5–14.5–14.6–14.6–14.5–14.6	14.55	69.4	30.6
22′	10–10–10.2–10–9.8–10	10.0	14–14.9–14.6–15–14.5–14.7	14.6	68.4	31.6
23′	9.5–9.5–9–9.5–9.5–9.5	9.4	14.9–14.2–15–14.3–14.4–14.8	14.6	64.3	35.7
24′	8.5–8.0–9.0–8.5–8.0–9.0	8.5	14–15–14.5–14–14.2–14.7	14.4	59.0	41.0
25′	7.0–5.0–6.0–6.0–5.5–6.5	6.0	13.8–14–14–14.2–14.1–13.9	14.0	42.8	57.2
26′	3.0–3.0–2.8–3.0–2.9–3.0	2.95	13.8–13.8–13.7–14–13.7–13.8	13.8	21.4	78.6
27′	1.5–1.5–1.5–1.5–1.5–1.5	1.5	14–14.5–14.3–14–14.5–14.5	14.3	10.5	89.5
28′	1.5–1.3–1.5–1.7–1.5–1.5	1.5	14–14–14.5–13.5–14–14	14.0	10.7	89.3
29′	4.5–4.8–4.5–4.8–4.6–4.7	4.65	14–14.5–14.5–14–14.5–14	14.25	32.6	67.4
30′	7.5–8.0–7.5–7.0–7.5–7.5	7.5	13.5–13.8–14–13.2–13.7–13.8	13.75	54.4	45.6

* At this point the prism was reset so as to give a greater amount of energy of the particular wave-length under study.

TABLE II

HCl Band at 3.4 μ (from curve of Fig. 3)

n	λ (in μ)	ν_n	$\Delta\nu_n$	ν_{on}	ν_{on} Computed	ν_{rn}	ν_{rn}/n
12.....	3.23868	3087.68					
			12.85				
11.....	3.25224	3074.83					
			13.27				
10.....	3.26631	3061.56					
			14.47				
9.....	3.28182	3047.09					
			15.89				
8.....	3.29903	3031.20					
			14.92				
7.....	3.31534	3016.28					
			16.30				
6.....	3.33336	2999.98					
			17.62				
5.....	3.35305	2982.36					
			17.38				
4.....	3.37270	2964.98					
			18.62				
3.....	3.39402	2946.36					
			18.35				
2.....	3.41529	2928.01					
			20.24				
1.....	3.43907	2907.77					
			41.60				
1'.....	3.48897	2866.17		2886.97	2886.73	20.80	20.80
			21.75				
2'.....	3.51565	2844.42		2886.22	2885.83	41.79	20.89
			22.48				
3'.....	3.54366	2821.94		2884.15	2884.33	62.21	20.73
			22.49				
4'.....	3.57214	2799.45		2882.21	2882.23	82.76	20.69
			23.04				
5'.....	3.60178	2776.41		2879.38	2879.52	102.97	20.59
			23.85				
6'.....	3.63298	2752.56		2876.27	2876.22	123.71	20.62
			23.67				
7'.....	3.66450	2728.89		2872.58	2872.32	143.69	20.53
			25.30				
8'.....	3.69878	2703.59		2867.39	2867.81	163.80	20.48
			25.03				
9'.....	3.73335	2678.56		2862.83	2862.71	184.26	20.47
			25.91				
10'.....	3.76982	2652.65		2857.11	2857.03	204.45	20.45
			26.15				
11'.....	3.80735	2626.50		2850.69	2850.67	224.16	20.38
			26.62				
12'.....	3.84633	2599.88		2843.78	2843.78	243.90	20.33

NOTE.—In this and succeeding tables and figures n refers to the number of the absorption maximum counting from the center of the band. The subscripts o and r refer to vibration and rotation, as in the "Discussion of Results." Wave-numbers are given throughout instead of actual frequencies. ν_n stands for $\nu_n/3\times10^{10}$.

remarked previously, since the interest has been only in the location of these maxima, and variations in pressure do not displace them laterally.

TABLE III

HCl Band at 1.76 μ (from curve of Fig. 5)

n	λ (in μ)	ν_n	$\Delta\nu_n$	ν_{on}	ν_{on} Computed	ν_{rn}	ν_{rn}/n
8.....	1.72711	5790.00					
			10.85				
7.....	1.73036	5779.15					
			12.58				
6.....	1.73413	5766.57					
			14.28				
5.....	1.73844	5752.29					
			14.18				
4.....	1.74274	5738.11					
			15.55				
3.....	1.74747	5722.56					
			16.58				
2.....	1.75255	5705.98					
			17.58				
1.....	1.75797	5688.40					
			42.03				
1'.....	1.77015	5646.37		5667.38	5666.38	21.01	21.01
			23.17				
2'.....	1.77835	5623.20		5664.59	5664.61	41.39	20.70
			23.16				
3'.....	1.78570	5600.04		5661.30	5661.67	61.26	20.42
			23.70				
4'.....	1.79329	5576.34		5657.22	5657.55	80.88	20.22
			25.80				
5'.....	1.80163	5550.54		5651.41	5652.25	100.87	20.17
			25.58				
6'.....	1.80997	5524.96		5645.77	5645.78	120.80	20.13
			26.64				
7'.....	1.81874	5498.32		5638.74	5638.12	140.42	20.06
			29.71				
8'.....	1.82862	5468.61		5629.31	5629.29	160.70	20.09

The 7500-line grating was used and the long-wave limit was determined by the strong atmospheric absorption beyond 4.2 μ, which cut down the galvanometer deflections to so small a figure as to magnify unduly any observational errors in computing the differential effect sought. It was possible, however, to obtain nine good maxima on the long-wave side of the center of the band. The curve is given in Fig. 6, and the table of values read and computed appears as Table IV.

A search was made for the "harmonic" of HBr at 2 μ found by Brinsmade and Kemble.[1] Nothing was found by any one of the three gratings, the conclusion being that the length of the

TABLE IV

HBr Band at 3.9 μ (from curve of Fig. 6)

n	λ (in μ)	ν_n	$\Delta\nu_n$	ν_{on}	ν_{on} Computed	ν_{rn}	ν_{rn}/n
9.....	3.72089	2687.53					
			11.82				
8.....	3.73133	2675.71					
			12.96				
7.....	3.75550	2662.75					
			13.46				
6.....	3.77460	2649.29					
			13.96				
5.....	3.79460	2635.33					
			13.46				
4.....	3.81407	2621.87					
			15.17				
3.....	3.83628	2606.70					
			15.37				
2.....	3.85902	2591.33					
			15.64				
1.....	3.88245	2575.69					
			33.59				
1'.....	3.93376	2542.10		2558.89	2558.93	16.79	16.79
			16.65				
2'.....	3.95969	2525.45		2558.39	2558.23	32.94	16.47
			18.05				
3'.....	3.98819	2507.40		2557.05	2557.08	49.65	16.55
			18.00				
4'.....	4.01704	2489.40		2555.63	2555.46	66.23	16.56
			18.49				
5'.....	4.04709	2470.91		2553.12	2553.38	82.21	16.44
			18.69				
6'.....	4.07793	2452.22		2550.76	2550.84	98.54	16.42
			19.33				
7'.....	4.11034	2432.89		2547.82	2547.74	114.93	16.42
			19.40				
8'.....	4.14338	2413.49		2544.60	2544.37	131.11	16.39
			20.19				
9'.....	4.17833	2393.30		2540.41	2540.44	147.11	16.35

column of absorbing gas was not great enough to give strong absorption in this region, nor was it possible in the time available to do the remodeling of the apparatus that a sensibly longer chamber would require.

[1] *Loc. cit.*

Hydrofluoric acid.—For the purposes of this study it was thought best to investigate a third gas of the halogen acid group. Of the two remaining, HF was thought the more likely to prove of theoretical value, and, aside from the difficulty of handling, easier to obtain in a pure state.

The inside of the absorption chamber was flowed with ceresin, as also was that of what tubing it was absolutely necessary to use. The gas was generated in a small iron retort by the action of concentrated H_2SO_4 on NaF. No attempt was made to dry it, but the absorption chamber was washed out with dry air before being filled with the HF, and the absence of any fuming as the gas entered the chamber was taken as evidence of the absence of

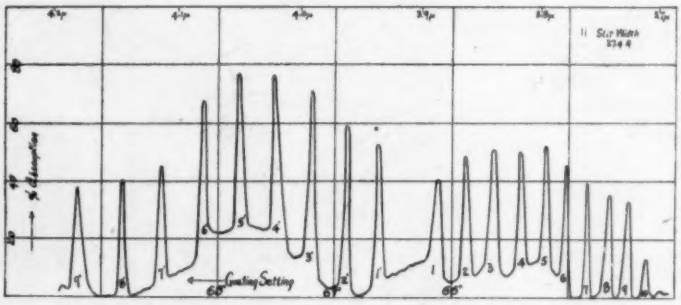


FIG. 6.—The HBr band at 3.9 μ, mapped with 7500-line grating

sensible amounts of moisture. Because of the gradual destruction of the surface of the plates used on the ends of the absorption chamber the percentages of apparent absorption ran gradually up until, usually at the end of from thirty minutes to an hour, it was necessary to change the plates. The expedient of spreading a thin layer of oil, grease, or even wax on the inner surfaces of the plates was tried, but greatly cut down their transparency in the region under study. This was doubly undesirable because on the long-wave side of the center of the band there is the very strong water-vapor band at 2.6 μ, which also cuts down the energy in spots so as to make the observational errors unduly large. It was here that a compensating chamber filled with dried air was thought of great importance. Also a new absorption chamber

was built, so designed that the plates could be clamped in place rather than cemented, thus saving much time in the necessarily frequent changes. Both mica and glass plates were used, those of mica proving the more satisfactory.

It is to be noted that the product of the action of HF on silica, present in both glass and mica, is a gas, SiF_4. In order to make certain that the absorption observed was not due to this second gas, observations were made at the beginning of each run with fresh plates, on one or more of the maxima previously obtained. If these had been absent or very much lowered the conclusion

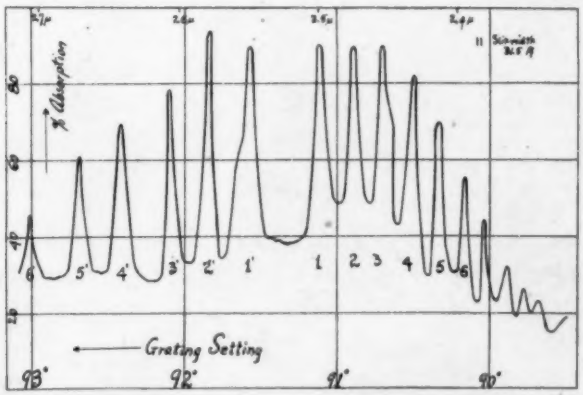


FIG. 7.—The HF band at 2.52 μ, mapped with 7500-line grating

would have been that they were due to SiF_4 which was then present in very small quantity. No such absence or lowering was observed.

The long-wave limit of this work was determined by the strong atmospheric (water-vapor) absorption beyond 2.6 μ, but it is to be noted that the number of maxima on the short-wave side of the center showing strong absorption is small as compared with that observed in the case of HCl.

The 7500-line grating was used in this work, except for the preliminary exploration done with the brass grating. The curve obtained for HF is given in Fig. 7, the measurements appearing in Table V.

A preliminary search was made for the possible "harmonic," to be expected in the region of 1.25 μ, but if it exists it was effectively masked by the rising general absorption due to the action of the gas on the windows of the absorption chamber.

TABLE V

HF Band 2.5 μ (from curve of Fig. 7)

n	λ (in μ)	ν_n	$\Delta\nu_n$	ν_{0n}	ν_{0n} Computed	ν_{rn}	ν_{rn}/n
7.....	2.37911	4203.25					
			28.56				
6.....	2.39539	4174.69					
			31.84				
5.....	2.41380	4142.85					
			32.35				
4.....	2.43280	4110.50					
			34.36				
3.....	2.45330	4076.14					
			36.24				
2.....	2.47531	4039.90					
			37.88				
1.....	2.49874	4002.02					
			80.17				
1'.....	2.54982	3921.85		3961.93	3961.71	40.09	40.09
			42.75				
2'.....	2.57791	3879.10		3959.50	3959.43	80.40	40.20
			44.41				
3'.....	2.60778	3834.69		3955.41	3955.63	120.72	40.24
			44.63				
4'.....	2.63848	3790.06		3950.28	3950.33	160.22	40.05
			46.06				
5'.....	2.67094	3744.00		3943.43	3943.49	199.42	39.88
			47.93				
6'.....	2.70557	3696.07		3935.38	3935.13	239.31	39.88

DISCUSSION OF RESULTS

Reference has been made to the variance between the assumptions of Bjerrum and of Ehrenfest with regard to the size of the quantum of rotational energy. From the newer point of view, which states more generally and precisely the postulate of stationary states, the Ehrenfest[1] equation may be justified. To do this use is made of A. Sommerfeld's[2] extension of the Planck phase-integral

[1] Proposed also by A. Eucken. See *Verhandlungen der deutschen physikalischen Gesellschaft*, **13**, 1159, 1913.

[2] *Annalen der Physik* (4), **51**, 1, 1916.

in which Sommerfeld splits up the general integral for f-degrees of freedom,

$$\int_{i=1}^{i=f} \Pi(dq_i dp_i) = h^f$$

(the q's are the position co-ordinates and the p's the corresponding momentum co-ordinates), into f separate integrals,

$$\int dq_i dp_i = h,$$

one equation for each degree of freedom. For a rotating diatomic molecule this quantum equation becomes

$$\int_o^{2\pi} I\omega_n d\theta = nh,$$

which must be regarded as a fundamental assumption.

In the case under consideration—that of rotation with constant angular velocity—this integral evaluates quite simply into

$$2\pi I\omega_n = nh,$$

which, written in terms of kinetic energy and rotation frequency, becomes the Ehrenfest equation,

$$\tfrac{1}{2} I(2\pi\nu_r)^2 = n\frac{h\nu_r}{2}.$$

From this equation there is obtained directly

$$\nu_r = n\frac{h}{4\pi^2 I}, \qquad (1)$$

giving rotation frequency in terms of the moment of inertia. This equation states that when the moment of inertia is constant, ν_r must have fixed values which are integral multiples of $h/4\pi^2 I$.

If, now, there is not the Maxwellian distribution of rotational velocities, but this series of frequencies differing by $h/4\pi^2 I$, it is evident that, still applying the combination principle, there would be expected in the near infra-red a series of pairs of absorption maxima corresponding to the frequencies $\nu_o \pm \nu_{rn}$ grouped symmetrically about ν_o, where ν_o is, as before, the frequency of vibration of the atoms within the molecule and ν_{rn} the rotation frequency corresponding to a given integral value of n.

Denoting the frequencies corresponding to a given pair of maxima by ν_n and $\nu_{n'}$ (the prime subscript referring to the long-wave side of the center of the band), ν_{rn} may be computed from the equations

$$\nu_n = \nu_0 + \nu_{rn},$$
$$\nu_{n'} = \nu_0 - \nu_{rn}, \tag{2}$$

whence

$$\nu_{rn} = \frac{\nu_n - \nu_{n'}}{2}. \tag{3}$$

The moment of inertia of the molecule will be, from equation (1),

$$I = n\frac{h}{4\pi^2\nu_{rn}}. \tag{4}$$

From the moment of inertia thus determined it is possible to compute the length of the molecule. Assuming the masses, m_1 and m_2, of the atoms concentrated at their nuclei which are a distance l apart,

$$I = \frac{m_1 m_2}{m_1 + m_2} l^2,$$

whence

$$l = \left(I\frac{m_1 + m_2}{m_1 m_2}\right)^{\frac{1}{2}}. \tag{5}$$

For $n = 1$, i.e., for molecules having one quantum of rotational energy, the following experimental values are obtained by means of equations (4) and (5):

TABLE VI

Molecule	$I \times 10^{40}$	$l \times 10^{8}$	$I \times 10^{40}$ (Kinetic Theory)
HF	1.37	.94	
HCl	2.64	1.28	2.45
HBr	3.27	1.42	3.35

Von Bahr[1] gives values of I and l for the HCl molecule computed from her experimental data and the Bjerrum hypothesis, differing from the values in the foregoing table by the factor 2 in the case of I and $\sqrt{2}$ in the case of l within very close agreement.

[1] *Philosophical Magazine* (6), **28**, 82, 1914.

Some check is desirable on any such values as these. In the present case the only one available is that furnished by the kinetic theory for the moment of inertia of a diatomic molecule in terms of its most probable rotational frequency. Accepting the equation previously given,

$$I=\frac{RT}{4\pi^2\nu_r^2N}, \tag{6}$$

and using the values obtained by Burmeister for the doublet maxima as corresponding to the most probable frequency through the equations $\nu_m=\nu_0\pm\bar{\nu}_r$, values may be obtained for the moments of inertia of HCl and HBr. (The present work, it is to be observed, furnishes no data for the determination of the most probable frequency.) Taking $R=8.26\times10^7$, $N=6.12\times10^{23}$, and $T=292°$, equation (6) gives:

$$\text{for HCl, } I=2.45\times10^{-40},$$
$$\text{for HBr, } I=3.35\times10^{-40}.$$

It may, indeed, be questioned whether this is a real check, but at any rate the agreement is significant.

If one turns to the curve of Fig. 3 and the accompanying table, Table II, it is at once apparent that the predicted symmetry of the maxima, i.e., the arithmetic progression expected in the frequencies of the maxima, does not exist. Instead, there is a gradual increase in frequency difference between two adjacent maxima as one goes farther into the infra-red.

Starting again with equations (2), the expression

$$\nu_0=\frac{\nu_n+\nu_{n'}}{2} \tag{7}$$

is obtained as giving the frequency of vibration of the molecule. A value of ν_0 computed from each pair of maxima appears in column 5 of the table. There are as many centers, then, as pairs of maxima, and the asymmetry of the band is the consequence of the shifting of these centers farther into the infra-red as the rotation velocity increases. In other words, it appears that

the vibration frequency of the atoms in the molecule is dependent on the rotation frequency of the molecule.

Denoting the series of vibration frequencies by ν_{on}, where n in the subscript refers to the number of the pair of maxima from which the value of ν_o is computed, and plotting ν_{on} against n, the curve of Fig. 8 is obtained. Fitting it to the equation $\nu_{on} = A - Bn^2$ by the method of least squares, the agreement between observed

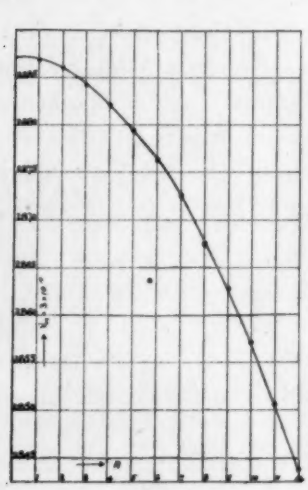


FIG. 8

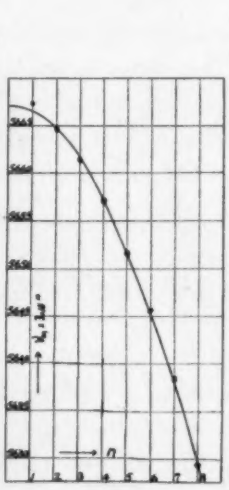


FIG. 9

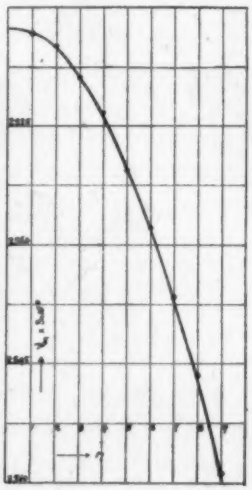


FIG. 10

FIG. 8. $\nu_{on} - n$ curve for the HCl band at 3.46 μ
FIG. 9. $\nu_{on} - n$ curve for the HCl band at 1.76 μ
FIG. 10. $\nu_{on} - n$ curve for the HBr band at 3.9 μ

and computed values shown in columns 5 and 6 of Table II is found. The equation of this curve is

$$\nu_{on}/3 \times 10^{10} = 2887.03 - 0.30n^2.$$

For ν_{oo}, the extrapolated center of the band, the value is of course A of the equation above, and the corresponding wave-length is 3.4637 μ, as against 3.475 μ obtained from the doublet maxima.[1]

Figures 9, 10, and 11 give respectively the parabolas of centers of the HCl band at 1.76 μ, the HBr band at 3.91 μ, and the HF band at 2.52 μ. From these curves Table VII is obtained:

[1] See Brinsmade and Kemble, *loc. cit.*

The last column of each of Tables II to V gives the experimental values obtained for ν_{rn}/n and confirms a previous observation of von Bahr that this value is not constant but decreases with increasing values of the rotation frequency. The variation is small, but as it appears in each of the four curves it cannot be regarded as accidental. Eucken suggests that this divergence from the constancy predicted by the Bjerrum formula is not due to a falsity of the formula but to an increase of the moment of inertia with the velocity of rotation. That such an increase does take place may be seen from the following values of the moment of inertia of the HCl molecule computed from the values of ν_{rn} given in Table II.

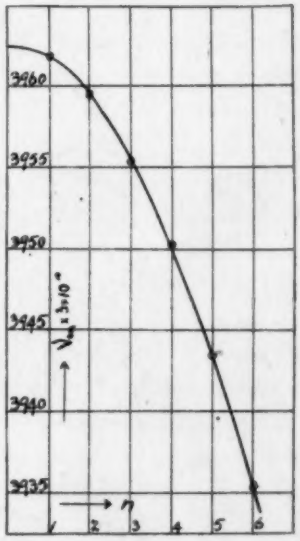


FIG. 11. $\nu_{on}-n$ curve for the HF band at 2.52 μ.

The relation between I_n and n is practically linear as shown by the equation obtained from the observed values above by the method of least squares,

$$I_n=(2.63+0.0055n+0.000007n^2)\times 10^{-40}.$$

The values computed from this equation (neglecting the term in n^2) are given parallel with the observed values in Table VIII.

The "harmonic."—Kemble[1] has advanced the theory that if the amplitude of vibration of the molecule be that required by even a single quantum the infra-red absorption bands discussed so far might be expected to be accompanied by faint harmonics. The center of the first harmonic according to this theory should be at one-half the wave-length of the center of the fundamental and the spacing of the doublet maxima should be one-fourth of that of the maxima of the fundamental doublet (in wave-length). A band approximately answering to these requirements had been observed by Burmeister in the case of carbon monoxide, and this

[1] *Physical Review* (2), **8**, 701, 1916.

was resolved into a doublet by Brinsmade and Kemble. They also obtained doublets for HCl and HBr approximately agreeing with the prediction. The disagreement was in the location of the centers, which were all farther in the infra-red than demanded by the theory.

Figure 5 gives the curve obtained for the HCl harmonic in the present work. The extrapolated value of the frequency of the center of this band is $5666.97 \times 3 \times 10^{10}$, while that of the center

TABLE VII

Band	$\nu_{0n}/3\times10^{10}$	Extrapolated Center	
		$\nu_{00}/3\times10^{10}$	λ_{00} (in μ)
HF	$3962.47-.76n^2$	3962.47	2.5237
HCl (3.46 μ)	$2887.03-.30n^2$	2887.03	3.4637
HCl (1.76 μ)	$5666.97-.59n^2$	5666.97	1.7646
HBr	$2559.16-.23n^2$	2559.16	3.9075

TABLE VIII

I_n	Observed	Computed
I_1	2.64×10^{-40}	2.636×10^{-40}
I_2	2.67×10^{-40}	2.641×10^{-40}
I_3	2.65×10^{-40}	2.647×10^{-40}
I_4	2.65×10^{-40}	2.652×10^{-40}
I_5	2.66×10^{-40}	2.658×10^{-40}
I_6	2.66×10^{-40}	2.663×10^{-40}
I_7	2.67×10^{-40}	2.668×10^{-40}
I_8	2.68×10^{-40}	2.674×10^{-40}
I_9	2.68×10^{-40}	2.680×10^{-40}
I_{10}	2.68×10^{-40}	2.685×10^{-40}
I_{11}	2.69×10^{-40}	2.690×10^{-40}
I_{12}	2.70×10^{-40}	2.696×10^{-40}

of the fundamental is $2887.03 \times 3 \times 10^{10}$, the ratio being 1.963:1 instead of the expected 2:1. Or, to compare the bands as Brinsmade and Kemble compare them, the center of the harmonic is found 0.033 μ farther in the infra-red than the predicted position. This displacement is greater than the width of all eight maxima on the short-wave side of the band and greater than that observed by Brinsmade and Kemble. It disposes at once of their explanation that the disagreement observed in their work might be due to a slight error in the dispersion curve on which

their wave-length measurements were based, since there is no uncertainty as to dispersion in the present observations, made with a grating.

It is interesting to note that the frequency differences between adjacent maxima at the centers of the two bands (fundamental and harmonic) are sensibly the same, as shown in column 4 of Tables II and III. Also the moment of inertia of the molecule computed by means of equation (4) is the same for fundamental and harmonic.

It is to be regretted that only this one harmonic was obtained, and it is to be hoped that others may be carefully measured in the near future. The apparent tendency of some of the maxima to resolve into doublets in the case of the HCl harmonic may be due to errors of observation, but it seems significant that the small secondary maxima are all on the long-wave side of the principal maxima which they accompany. It is, of course, possible that still higher dispersion applied to the problem may show even the present curves to be composite.

Accuracy.—The question of the accuracy attained in such a problem as this is of necessity quite involved. An adequate estimate, however, of the accuracy of the determinations of the positions of the absorption maxima may be obtained by reference to columns 5 and 6 of Tables II to V inclusive. Column 5 of each table gives the frequency of the centers of the various pairs of maxima of the accompanying curves from wave-length readings on the curves. Column 6 of each table gives the values for the same centers computed by the method of least squares. In the case of Table II, the greatest variation of the observed value from the computed value is in the case for $n=8$, where $d\nu=0.42\times3\times10^{10}$. This corresponds to a value of $d\nu$ given by the equation

$$d\lambda=\frac{c}{\nu^2}d\nu.$$

Substituting the values $\nu=2872.6\times3\times10^{10}$ and $d\nu=0.42\times3\times10^{10}$, it is found that

$$d\lambda=5\times10^{-8}\text{ cm}=5\text{ A.}$$

This is the extreme case. The average agreement is within ±1.9 A.

SUMMARY

The object of the present work has been to obtain more extended and more accurate data with regard to the near infra-red absorption bands of certain diatomic gases than have been hitherto available. To this end the closely related HF, HCl, and HBr bands have been mapped, using greater dispersion than has been used before in this particular problem.

Curves are presented showing in greater detail the HCl bands at 1.76 μ and 3.46 μ and giving for HBr, instead of the simple doublet hitherto known, a curve resolved into its quantum lines. In addition, a similar curve is presented for HF which has not been studied before.

Several peculiarities in these curves are pointed out for the first time and one or two uncertainties in previous work are settled by material presented here.

From experimental results the lengths and moments of inertia of these three molecules have been computed.

It is hoped that in the material presented there will be found some of real value in the work which is yet to be done in reconciling theory and fact in the extremely interesting field of molecular mechanics. It is a very real pleasure to acknowledge the writer's indebtedness to Professor Randall, who suggested the problem, for his continued interest and encouragement during the progress of the work.

PHYSICAL LABORATORY
UNIVERSITY OF MICHIGAN
April 30, 1918

ON PROGRESSIVE CHANGES OF THE WAVE-LENGTHS OF LINES IN STELLAR SPECTRA WITH CHANGE OF TYPE

By SEBASTIAN ALBRECHT

In the *Astrophysical Journal* for March 1918 (**47**, 137) J. Voûte published the results of an investigation which was undertaken in order to ascertain to what extent stellar wave-lengths determined with the McClean telescope of the Royal Observatory, Cape of Good Hope, show relative changes with type of the kind previously announced by the present writer.[1] Voûte selected four stars for this purpose, namely: α Canis Majoris, type Ao; α Canis Minoris,[2] type F5; α_2 Centauri, type Go; and α Boötis, type Ko. The number of plates measured were respectively 10, 5, 8, and 10. Voûte concludes that his wave-lengths agree in general fairly well with mine, the most pronounced progressions being generally confirmed by his observations.

F. E. Baxandall, discussing the two sets of wave-lengths in the July number (**48**, 59), apparently concludes that the agreement is not so good as might be desired, and that the subject deserves further attention.

As apparently both Voûte and Baxandall are unaware of a somewhat more complete and slightly revised list of wave-lengths, though still entirely preliminary, published by the writer in *Boletin No. 1* of the Córdoba Observatory, it seemed worth while to make a more detailed comparison of my wave-lengths and those of Voûte. I shall confine the comparison to published data.[3]

[1] The expression "progressive changes" has been used by the writer in the sense of progressing continuously with the sequence of types, i.e., without any discontinuities, but also without any restrictions whatever as to the direction in which the wave-length may vary. Thus changes in direction of variation are not excluded and in fact have been observed for numerous lines.

[2] Harvard gives F5 as the type for this star; Voûte calls it F.

[3] I have accumulated a considerable amount of additional data, for which the completion of the reductions and the publication have been unavoidably delayed.

It may be appropriate to recall briefly that there are strong indications that the physical conditions in the stars as we pass from type A to type Mb vary roughly in the same direction as from sun to sun-spots. The solar spectrum very closely resembles the spectrum of a G-type star. Adams has shown that a striking similarity exists in the intensities of sun-spot lines and of the corresponding lines in the spectrum of Arcturus, a K-type star. This refers to the intensities of the lines and of the components of lines. It is a well-known fact that in the series of stellar spectra lines change progressively in intensity. Some lines which are strong in the so-called early types become weaker and often disappear entirely as we pass to the later types. In fact, our systems of stellar classification depend upon the presence or absence and changing intensities of the spectrum lines. Thus changes which are progressive with change of type are normally to be expected, and changes which are apparently abrupt or discontinuous would, to a considerable degree, contain the presumption of abnormality and would lead one to look for additional effects superimposed upon the changes dependent on spectral type. Thus recent work by Mount Wilson observers indicates a dependence of line-intensity, for certain lines, upon the absolute luminosity of the star and possibly also upon distance. Other factors are involved which help to complicate matters. For example, the best available evidence seems to indicate that great differences in absolute luminosity are accompanied by great differences in stellar density and therefore in size. Accompanying differences in size, it is a natural step to infer also considerable differences in the depths of the reversing layers and in the pressures and other factors, which in turn will give rise to spectral differences in the integrated stellar light secondary to the main spectral characteristics. Some of the changes of line-intensity which are thus introduced are likely to involve line displacements of the order of magnitude considered in this note, especially when blended with other components. Therefore in extensive studies of changes of wave-length with type such effects will have to be taken into account, and, besides separating the stars according to type, they must be separated also according to other factors, such as absolute luminosity. The limited comparison made below is not

likely to be appreciably changed by partly neglecting these distinctions.

In Table I, which is largely self-explanatory, are given the lines for which both Voûte and I have published wave-lengths. The weights were assigned more or less arbitrarily according to suitability for determining the difference (Albrecht−Voûte), and were increased by 50, 75, or 100 per cent, according as both observers have measures respectively for the same two, three, or four types. My wave-lengths are taken from curves drawn to represent best the wave-lengths observed for each type (*loc. cit.*); those of Voûte are from his published list (*loc. cit.*), corrected to my system by

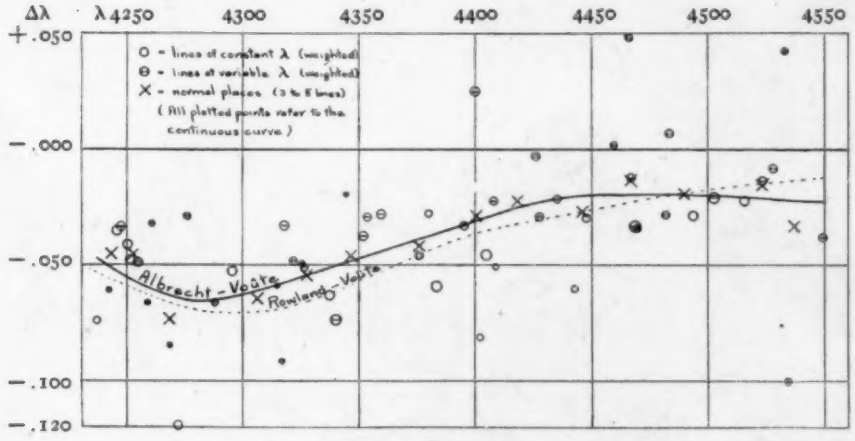


FIG. 1

means of the corrections Δλ shown in column 3. These corrections, which were applied purely to facilitate the intercomparison, do not differ greatly from those required to reduce Voûte systematically to Rowland, as is seen from the figure. The small difference between the two curves represents mostly a small systematic difference, for this particular group of lines, between myself and Rowland. The reasons for the large systematic deviation of Voûte from Rowland cannot be gone into without having available the complete details of the reductions. Moreover, we are here concerned primarily with the changes in the wave-lengths depending on stellar type rather than with the systematic differences between the two observers.

TABLE I

λ.	Weight	Albrecht Voûte	Corr. Applied (Δλ)	Wave-Lengths (By A and V) Ao	F5	Go	Ko	Constant	No. of Obs.	Rowland λ in Sun	Blend According Intensities	Rowland Inten. in Sun	Inten. in Sun-Spots (Adams)	Enhanced (Lockyer) El.	Spark	Arc	Remarks
4236.0...	1	A	.....	.....	.....	.....	.....	A5 to Mb									
		V	−.05	.10	.....	.14	.07	.079	26	.112		Fe 8	n.c.	.....	.....	.....	Principally Fe. The companions are relatively too weak to blend satisfactorily.
								.....	.....	.279		1					
								.....	.....	.429		Ni 1					
4242.5...	½	A	.....	.509	.530	.....	.....	.....	11	.322		0	.....	.....	.....	.....	In types A and F principally the spark lines of Mn and Cr.
		V'	−.05	.52	.....	.61	.....	.....	.....	.443		0	0	Mn	4	0	In types G and K not measured on account of the numerous components. In M the spark lines probably absent.
										.535		2		Cr	6–7	0	
										.615		2					
										.766	.703	2					
										.897		Fe 2					
								F to Mb									
4245.4...	1½	A	.....	.....	.....	.....	.....	.438	36	.243		ON	.....	Bis	3	0	A good line for radial-velocity work with three prisms.
		V	−.05	.....	.41	.43	.43	.....	.....	.422	.455	Fe 4	8				
										.520		2					
4246.9...	1½	A	.....	.....	.993	.986	.973	.....	40	.729		ooo	.....	Mo	1	0	The shift toward the violet, though small, seems definite. Cause not apparent.
		V	−.05	.....	.96	.96	.98	.....	.....	.996		Sc 5	3				
4250.2...	1½	A	.....	.....	.....	.....	.....	A5 to Mb									
		V	−.06	.....	.26	.27	.30	.296	44	.2875		Fe 8	7	.....	.....	.....	A good line for radial-velocity work with three prisms.
4250.9...	1½	A	.....	.....	.....	.....	.....	A5 to Mb									
		V	−.06	.....	.93	.94	.96	.955	43	.863		0	.....	Mo	6	2	Lockyer gives for Mo λ .90 or .85. The stellar line is good for radial-velocity work with three prisms.
								.....	.....	.945	s	Fe 8	n.c.				
								.....	.....	.071		1					
4254.5...	1½	A	.....	.....	.504	.502	.498	.....	39	.5058		Cr 8	10	.....	.....	.....	In sun-spots "widened, prob. winged." In K types the line is broad and fuzzy toward the violet.
		V	−.06	.....	.48	.50	.49										
4258.4...	½	A	.....	.....	.....	.....	.494	.....	.....	.201		Zr 0	.....	Zr	2–3	1	A very broad blend. In types K to Mb practically no change in λ.
		V	−.06	.....	.....	.....	.50	.....	.....	.219		1N	0–1				
										.477		Fe 2	4				
										.639		ON					
										.774		Fe 2					
4260.6...	½	A	.....	.....	.643	.658	.712	.....	18	.151		Fe 2	.....	.....	.....	.....	Fe λ .640 is "apparently narrowed" in sun-spots. It seems likely that Voûte's λ in G is a v. broad blend, including λ .15 and λ .28. The observed change in wave-length with type needs strengthening by additional measures.
		V	−.06	.61	.67	.51	.75	.....	.....	.282	.50	Fe 3d?					
										.494		ON					
										.640	s	Fe 10	8				
										.768		ON					
										.888		1					
										.991		Ti 0					

4267.9...	½	A	+.093	....	.964	.986	.045	.....	15	.900		I	.....	....	.....	.....	My published wave-lengths for this line are in error by −.091 A. Apparently Fe is weakened, and either Zr or line to red much strengthened.
		V	−.06	....	.....	.....	.07	.....	.....	.985		Fe 3					
										.138		Zr 0					
										.266		IN					
								F to Mb									
4271.3...	1½	A	.....	.....	.....	.....	.....	.322	22	.212		ON	.....	....	.....	.....	My observed wave-lengths, with no. of obs., are: F, .317₈; F5 and F8, .319₅; G, .352₂; G5, .321₁; K, .304₄; K2 and K5, .319₂; Ma and Mb, .319₈.
		V	−.06	.31	.28	.38	.49	.....	.....	.325		Fe 6	5				
										.538		0					
4274.9...	1½	A	.....	.....	.962	.955	.950	.....	39	.746	.911	Ti 2	12	....	.....	.....	In sun-spots "much widened to violet." Shift to violet not as great as expected.
		V	−.06	....	.92	.90	.95	.....	.....	.958		Cr 7d?					
4288.1...	1	A	.....	.....	.122	.143	.166	.....	38	.038		Ti 2	.....	.....	.....	.....	Lockyer gives λ for Ru as .15 or .20. Probably all of the components vary in intensity. Shift toward red is quite definite.
		V	−.06	....	.11	.14	.20	.....	.....	.149	.134	Ni 1	.....	Ru	1	0	
										.310		Ti, Fe 1	2				
								A5 to Mb									
4294.2...	1½	A	.....	.....	.....	.....	.....	.277	30	.077		ooo	.....	Ru	3	0	A weakening of the enh. Ti component might be expected in the late types, but no corresponding shift to the red is shown in either set of measures.
		V	−.06	.27	.27	.26	.28	.....	.....	.204	.273	Ti 2	8	Ti	7	3	
										.301		Fe 5					
4314.3...	½	A	.....	....	.331	.339	.371	.....	30	.248		Sc 3	2	....	.....	.....	The changes in direction of variation of λ in types require verification by additional measures.
		V	−.06	....	.....	.....	.37	.....	.....	.381	.321	I					
										.479		Ti 1					
										.673		ON					
4315.1...	1	A	.....	....	.186	.176	.151	.....	49	.964		Ti 1	2-3	....	.....	.....	The shift to violet is quite definite and is caused by the relative greater strengthening of λ .964 than of λ .262.
		V	−.06	.21	.28	.18	.15	.....	.....	.138	.178	Ti 3	2	Ti	8	1	
										.262		Fe 4	5				
4318.8...	1½	A	.....	....	.850	.864	.882	.....	78	.8178		Ca, Mn? 4	6	....	.....	.....	"Winged" in sun-spots. Hasselberg gives a Ti component (Kilby), spark 3, arc 5. Average variation of λ with type is small.
		V	−.06	....	.79	.86	.87										
4321.0...	1½	A	.....	....	.002	.975	.930	.....	34	.907	.992	Sc 3	3	....	.....	.....	Shift to violet expected as the red component is a spark line and is weakened in sun-spots.
		V	−.06	....	.97	.96	.93	.....	.....	.119		2	1	Ti	3	1	
4325.1...	1	A	.....	....	.186	.183	.225	.....	35	.977		0	.....	....	.....	.....	The usual strengthening of Ti and Cr in the later types accounts for the general shift to the red. The cause for my secondary alternating shifts, if real, is not so apparent. Possibly Voûte's λ in F5 is Sc alone?
		V	−.06	....	.11	.21	.24	.....	.....	.152	.183	Sc 4	6				
										.306		Ti, Cr 1					
										.516		Ni, Zr 1					

TABLE I—*Continued*

λ	Weight	Albrecht Voûte	Corr. Applied (Δλ)	Wave-Lengths (By A and V) Ao	Fs	Go	Ko	Constant	No. of Obs.	Rowland λ in Sun	Blend According Intensities	Rowland Inten. in Sun	Inten. in Sun-Spots (Adams)	Enhanced (Lockyer) El.	Spark	Arc	Remarks
4325.9...	1½	A	.....	....	.959	.984	.975	.....	39	.777		1	.....	....	.....	.....	The Fe line is "apparently narrowed in spots" and is much sharpened at the limb. My wave-lengths for the M type need strengthening.
		V	−.06	.94	.93	.96	.00	.....	.....	.9398	.941	Fe 8	7				
										.119		1					
										.213		0					
								F to Mb									
4337.2...	1½	A	.....	....	....	....	....	.227	36	.216		Fe 5	6	....	.....	.....	"Winged" in sun-spots. Red edge frequently fuzzy in stars, probably on account of the faint companion.
		V	−.05	....	....	.24	.24	.....	.....	.414		0					
4340.6...	2	A	.....	.648	.659	.658	.638	.....	77	.192		000	.....	K	2	0	Hγ is "weakened and narrowed on red edge mainly" in sun-spots. The wave-length drops off very rapidly from K2 (.628) to Mb (.560), Hγ being faint in Mb and blended into a broad and fuzzy line with Cr λ .297. The wave-lengths of Voûte and Albrecht are in fair agreement, except in F5.
		V	−.05	.66	.73	.68	.63	.....	.....	.297		Cr 0	0–1				
										.634		Hγ 20N	8				
										.7 or .8		.....	.....	Bis	5	0	
4344.5...	½	A	.....	....	.550	.576	.621	.....	50	.451		Ti −2	n.c.	Ti	3	1	The observed shift to the red is in accord with the indicated strengthening of Cr in sun-spots. Also, the Ti line is weakened at the limb.
		V	−.05	....	....	....	.59	.....	.....	.670	.597	Cr 4	6				
4351.9...	1½	A	.....	.981	.019	.019	.008	.....	80	.711		Fe 2	.....	.....	.....	.....	For blend in sun-spots, "strengthening very doubtful." The Mg line is very slightly weakened in sun-spots, and is weakened and moderately sharpened at the limb. Albrecht's observed stellar wavelengths may find an explanation in a moderate weakening of λ .930 in F and G due to a great weakening of the Fe spark line and a strengthening of Cr, and a slightly preponderating weakening of λ .083 in K and M due to a slight weakening of Mg and a considerable strengthening of Cr.
		V	−.05	.99	.01	.98	....	.....	.....	.871		0000					
										.930		Cr, Fe 5	11	Fe	5	0	
										.083	.006	Mg 5 Nd?					
										.235		0N					

4352.9...	1½	A	.....	....	.936	.947	.975	.....	53	.718		ON	.....	.....	.....	.....	The blend (Fe, V) is "widened to red" in sun-spots. Probably the vanadium component is principally responsible for the observed shift to the red in stars. The wave-length in Mb may indicate an appreciable weakening of Fe?
		V	−.05	.....	.....	.91	.97	.....	.....	.9088		Fe 4	5				
										.044		V 0	7				
4359.8...	1½	A	.....	....	.803	.784	.798	.....	64	.654		Ni 0		Zinc	3	0	The curve representing the wave-lengths is weak from A5 to F5, but strong and well determined from G to Mb. Cause for the observed shift is not apparent.
		V	−.04	....	.80	.76	.79	.....	.....	.7848		Cr 3	5				
										.907		Zr 0		Zr	4	1–2	
								F to Mb									
4376.1...	1½	A	.....	.....	.....	.....	.....	.104	56	.1078		Fe 6	8	.....	.....	.....	"Probably winged" in sun-spots. Consistently small range within each type. Very good for radial-velocity work with three prisms.
		V	−.04	.....	.....	.08	.14										
								G to Mb									
4379.3...	1	A	.....	.....	.....	.....	.....	.383	43	.396		V 4	7	.....	.....	.....	"Very broad" in sun-spots.
		V	−.04	.....	.....	.....	.37										
								A to Mb									
4383.7...	2	A	.....	.....	.....	.....	.....	.721	70	.7208		Fe 15	n.c.	.....	.....	.....	In the M types strong, broad, and usually fuzzy, but not shifted.
		V	−.04	.72	.72	.74	.78										
4395.2...	1½	A	.....	.203	.244	.255	.276	.....	104	.201	.286	Ti 3	2	Ti	9	5	The definite shift toward the red is due to the strengthening of the component to the red and a weakening of the component to the violet.
		V	−.03	.21	.22	.27	.29	.....	.....	.413		V, Zr 2	3				
4399.9...	1½	A	.....	.948	.931	.917	.885	.....	66	.776		Ni 0	.....	.....	.....	.....	In the A type the line is practically the Ti spark line alone; in F and later types it is a blend with Cr and possibly also Ni. Three measures in α_2 Centauri give λ .89.
		V	−.03	.95	.87	.81	....	.....	.....	.935		Ti, Cr 3	2	Ti	7	3	
								F to Ma									
4401.6...	1	A	.....	.....	.....	.....	.....	.613	44	.456	.589	Fe 2	.....	.....	.....	.....	Although from F to Ma my wave-length is apparently constant and in fair agreement with the blend according to Rowland's intensities in the sun, in Mb I obtain λ .71 for a "faint, broad, and very fuzzy" line.
		V	−.03	.....	.....	.67	.66	.....	.....	.613		Fe 1					
										.709		Ni 2					
								A to Ma									
4404.9...	2	A	.....	.....	.....	.....	.....	.932	63	.9278		Fe 10	9	.....	.....	.....	Rowland gives very faint companions on each side, which apparently do not become effective in stellar spectra.
		V	−.03	.94	.94	.97	.94										
4407.8...	1½	A	.....	.....	.857	.853	.843	.....	54	.810	.851	V 2	8	.....	.....	.....	The stellar line is principally Fe in F type and V in Mb.
		V	−.03	.....	.....	.81	.87	.....	.....	.8718		Fe 4					

TABLE I—*Continued*

λ	Weight	Albrecht Vo0te	Corr. Applied (Δλ)	Wave-Lengths (By A and V) Ao	F5	Go	Ko	Constant	No. of Obs.	Rowland λ in Sun	Blend According Intensities	Inten. in Sun	Inten. in Sun-Spots (Adams)	Enhanced (Lockyer) El.	Spark	Arc	Remarks
								A8 to Mb									
4408.5...	2	A	.....	....	....	....	....	.579	43	.364		V 2	3–4	....	.....	.....	My observed stellar wave-lengths show no shift with type, nor is much shift to be expected where the components on each side vary together in intensity.
		V	−.03	....	....	.62	.58	.....	.....	.582	.549	Fe 3	7				
										.683		V 2					
4425.6...	1½	A	.....	....	.615	.660	.872	.....	29	.6088		Ca 4	5–6	....	.....	.....	"Winged" in sun-spots. Variation of λ in F and G weakly determined. In K and M the measures represent a blending with λ 26.201, forming a very broad double line, resolved with moderate slit widths.
		V	−.02	....	.60	.64				.201		Ti on d?					
4427.4...	1½	A	.....	....	.449	.443	.432	.....	78	.266		Ti 2	3	....	.....	.....	My wave-lengths show a small but definite shift, indicating that the strengthening of the weaker component is more effective than the strengthening of the stronger.
		V	−.02	....	.45	.44	.46	.....	.....	.482	.420	Fe 5	7				
4435.1...	1½	A	.....	....	.160	.186	.230	.....	62	.1298		Ca 5	7	....	.....	.....	Shift to red in stars is quite definite, showing that the strengthening of the weak component is more effective than the strengthening of the strong component.
		V	−.02	....	.15	.20	.23	.....	.....	.321	.184	Fe 2	3				
								A5 to Mb									
4442.5...	1	A	.....	....	....	....	....	.529	66	.510		Fe 6	7	....	.....	.....	
		V	−.02	....	....	....	.57										
								A5 to Mb									
4447.9...	1½	A	.....	....	....	....	....	.915	74	.8928		Fe 6	7	....	.....	.....	"Winged" in sun-spots. The stellar line may possibly be shifted slightly toward the violet in the M type.
		V	−.02	....	....	.92	.93										
4459.2...	1	A	.....	.226	.302	.317	.327	.....	103	.199		Ni 2	7	....	.....	.....	Cr is "widened" in sun-spots. Shift of blend is small in types F5 to M. Blend shifted back slightly toward the violet in Mb?
		V	−.02	....	.30	.27	.31	.....	.....	.301	.304	Fe 3					
										.525		Cr 1	1–2				
4464.6...	1	A	.....	.609	.749	.811	.885	.....	21	.617		Ti? 2	n.c.	Ti	3	1	In the A type the observed λ is that of Ti alone. The large shift toward the red in the K types seems to imply also a weakening of the Ti component?
		V	−.02	....	.69	.75	.80	.....	.....	.844	.772	Mn 2	3–4				
										.938		Fe 1					
4466.7...	1½	A	.....	....	.743	.749	.779	.....	63	.548		Ni 0	.....	.....	.....	.....	Fe "widened and hazy" in sun-spots.
		V	−.02	....	.73	.74	.78	.....	.....	.727		Fe 5	7	K	1	0	The stellar wave-lengths show the widening to be principally toward the red.

4468.6...	2	A	.....	.662	.651	.660	.695	.....	117	.663		Ti– 5	4	Ti	9	4	Variation of λ in stellar spectra is quite definite. It may be a blend?
		V	−.02	.69	.66	.66	.71										
4469.4...	1	A	.....	.....	.496	.530	.593	.....	44	.316		Ti 1	0–1	.....	.....	.....	Fe is "narrow, probably winged," in sun-spots. Variation with type seems quite definite. In the F type λ .316 and in the M type one or more of the components to the red probably become effective with λ .545.
		V	−.02	....	.51	.54	.61	.....	.....	.441		0000					
										.545		Fe 4	4				
										.731		Co o d?					
										.873		V ∞	0				
4481.3...	1½	A	.....	.381	.395	.400	.410	.....	160	.298		0	000	Mg	10	0	A slight increase in λ with type seems indicated. Shall discuss this line in detail at another time.
		V	−.02	.43	.41	.36	....	.....	.....	.438		Ti 1	2				
										.515		0					
4482.3...	1½	A	.....	.....	.393	.394	.393	.....	57	.338	.376	Fe 5	11	.....	.....	.....	My stellar wave-lengths are practically constant from F to K but diminish rapidly from K2 to Mb.
		V	−.02	....	.36	.35	.39	.....	.....	.438		Fe 3					
								A5 to Mb									
4494.7...	1½	A	.....	.....	.....	.....	.....	.714	30	.548		00	.....	Zr	2–3	0	Lockyer gives a spark line of Zr at λ .55 or λ .78. In stellar spectra this line is fuzzy on one or both edges, and therefore not especially good for radial-velocity work.
		V	−.02	....	.74	.70	.73	.....	.....	.656		00					
										.7388		Fe 6	8				
										.903		000					
4501.4...	2	A	.....	.444	.437	.435	.430	.....	75	.264		Cr, Mn o	.....	.....	.....	.....	The indicated small progressive variation with type is still uncertain.
		V	−.02	.49	.45	.37	.44	.....	.....	.4458		Ti– 5	3	Ti	8	4	
										.622		00N					
										.7 or .8		.....	.....	.....	4–5	0	Caesium spark line.
								A to Mb									
4515.5...	1½	A	.....	.....	.....	.....	.....	.517	46	.342		0					
		V	−.02	.61	.48	.47	....	.....	.....	.508		3	1	Fe	4	trace	
4522.7...	1½	A	.....	.795	.847	.861	.830	.....	48	.691		Fe? o	.....	.....	.....	.....	The observed shift to the red is to be expected, due to weakening of the spark line and strengthening of the Ti component. Cause for drop in λ in K type (if real) is not apparent.
		V	−.02	.82	.82	.80	.87	.....	.....	.802	.871	3	1	Fe	6	2	
										.974		Ti 2	4				
4528.7...	1½	A	.....	.741	.794	.810	.825	.....	43	.647		ON	n.c.	V	6	1	Vanadium spark line at λ .70 or λ .73. The change in wave-length is most rapid in types A to G. In types later than G the vanadium spark line has practically ceased to be effective. This is in accord with the indicated no change in sun-spots.
		V	−.02	....	.79	.79	....	.....	.....	.798		Fe 8					
										.929		0					
										.990		0					
4533.2...	1	A	.....	.....	.288	.301	.336	.....	34	.133		1	.....	.....	.....	.....	The observed shift toward the red is accounted for by the expected strengthening of the Ti spot line. In M the violet components seem to be relatively too faint to be in the least effective.
		V	−.02	....	.20	.27	.27	.....	.....	.219		0					
										.419		Ti 4	5–6				
4534.1...	1	A	.....	.195	.190	.186	.175	.....	48	.139	.168	Ti-Co 6	5	Ti	5	2	Although a small shift toward the violet seems indicated, many more measures are required to establish it.
		V	−.02	.23	....	.31	....	.....	.....	.340		1					
4549.6...	1½	A	.....	.685	.736	.753	.783	.....	88	.642	.776	Fe 2	0	Fe	7	1	The shift toward the red is due to the more rapid weakening of the violet component, which seems to have practically disappeared in Mb.
		V	−.02	.65	.81	.75	.82	.....	.....	.808		Ti-Co 6d?	4	Ti	8	4	
										.990		0					

Table II has been prepared to bring out the fact that the differences (Albrecht−Voûte) run practically the same for the lines of constant wave-length (Albrecht's) as for the lines for which the wave-length changes with spectral type. The slight difference in

TABLE II

(Albrecht−Voûte), in Units of 0.01 A

Constant Lines						Variable Lines					
λ	Ao	F5	Go	Ko	Range	λ	Ao	F5	Go	Ko	Range
4236.0	−2	.....	−6	+ 1	7	4245.2	−1	.....	.....	.....	.....
4245.4	.....	+3	+1	+ 1	2	4246.0	.....	+3	+ 3	−1	4
4250.2	.....	+4	+3	0	4	4254.5	.....	+2	0	+1	2
4250.9	.....	+2	+1	− 1	3	4260.6	.....	−3	+15	−4	19
4258.4	.....	.....	.....	− 1	.....	4267.9	.....	.....	.....	−2	.....
4271.3	(+1)	+4	−6	−17	21	4274.9	.....	+4	+ 6	0	6
4294.2	(+1)	+1	+2	0	2	4288.1	.....	+1	0	−3	4
4337.2	.....	.....	−1	− 1	0	4314.3	.....	.....	.....	0	.....
4376.1	.....	.....	+2	− 4	6	4315.1	.....	−9	0	0	9
4379.3	.....	.....	.....	+ 1	.....	4318.8	.....	+6	0	+1	6
4383.7	0	0	−2	− 6	6	4321.0	.....	+3	+ 2	−1	4
4401.6	.....	.....	−6	− 5	1	4325.1	.....	+8	− 3	−2	11
4404.9	−1	−1	−4	− 1	3	4325.9	.....	+3	+ 2	−2	5
4408.5	.....	.....	−4	0	4	4340.6	−1	−7	− 2	+1	8
4442.5	.....	.....	.....	− 4	.....	4344.5	.....	.....	.....	+3	.....
4447.9	.....	.....	0	− 1	1	4351.9	−1	+1	+ 4	.....	5
4469.4	.....	−1	−1	− 2	1	4352.9	.....	.....	+ 4	0	4
4494.7	.....	−3	+1	− 2	4	4359.8	.....	0	+ 2	+1	2
4515.5	−9	+4	+5	.....	14	4395.2	−1	+2	− 2	−1	4
						4399.9	0	+6	+11	.....	11
						4407.8	.....	.....	+ 4	−3	7
						4425.6	.....	+2	+ 2	.....	0
						4427.4	.....	0	0	−3	3
						4435.1	.....	+1	− 1	0	2
						4459.2	.....	0	+ 5	+2	5
						4464.6	.....	+6	+ 6	+8	2
						4466.7	.....	+1	+ 1	0	1
						4468.6	−3	−1	0	−2	3
						4481.3	−5	−2	+ 4	.....	9
						4482.3	.....	+3	+ 4	0	4
						4501.4	−5	−1	+ 6	−1	11
						4522.7	−2	+3	+ 6	−4	10
						4528.7	.....	0	+ 2	.....	2
						4533.2	.....	+9	+ 3	+7	6
						4534.1	−4	.....	−12	.....	8
						4540.6	+4	−7	0	−4	11
Means (without sign)	2.3	2.3	2.5	2.7	5.0		2.5	3.2	3.5	2.0	5.9
Means (with sign)	−3.0	+1.3	−0.9	−2.3	.....		−1.7	+1.2	+2.2	−0.3	.....

favor of the constant lines may be attributed to the fact that these lines are on the average more nearly "pure," i.e., single components, than the lines of variable wave-length. Sixty-three per cent of the constant lines and 33 per cent of the variable lines are apparently pure. Also the average weight assigned according to suitability for determining the difference (Albrecht−Voûte) is 0.88 for the

constant lines and 0.74 for the variable lines. Table II also shows up the moderate systematic differences for the individual types. A few exceptionally large values appear in the table, some of which, like that for 4260.6, are probably due to the inclusion by one observer of components excluded by the other. Such differences are to be expected, as accurate descriptions of the lines have not yet been published. The large difference of 0.17 A for the pure line 4271.3, due to the large deviation of Voûte's wave-length from that of Rowland seems inexplicable. The deviation seems too large to be attributed to personality in the settings due to the close proximity of the strong line 4271.9.

The comparison of the two sets of stellar wave-lengths can best be followed by referring to the corresponding data in Tables I and II. In Table I the columns giving the components in the solar spectrum (Rowland), the intensities in sun-spots, and the behavior in spark and in arc spectra aid in indicating the degree to which the wave-lengths observed in stellar spectra correspond to the wave-lengths which might by inference be expected. For the writer's wave-lengths this correspondence is quite close, with very few exceptions—see also remarks in Table I—both for the G type and, in direction and approximate amount, for the other types. While Voûte's wave-lengths also correspond in a general way they show more frequent and larger deviations.

On the whole, I believe that Voûte's wave-lengths do confirm my variations with type. In considering this question we should bear in mind, especially as Voûte's wave-lengths are given to only two decimal places, that a considerable range of accidental variation in the differences (Albrecht−Voûte) must be anticipated, so that only a comparatively few lines—those with a large range of variation with type—are competent individually to give fairly definite evidence. Among these may perhaps be included 4288.1, 4321.0, 4395.2, 4435.1, 4464.6, 4469.4, and 4549.6. The line 4468.6, though especially good for variation with type, has only a moderate range of variation from A to K.

An inspection of my tables will show that most of Baxandall's criticisms do not strictly apply. In paragraph 2 Baxandall interprets my use of the word "progressive" in a sense different from

that clearly implied in my tables of wave-lengths and in my curves showing the variations for individual lines. This also accounts for Baxandall's third paragraph in so far as it refers to complex blends involving more than two components. For the three complex blends 4288.1, 4315.1, and 4352.0, which were cited, the agreement between Voûte and Albrecht is satisfactory, except in F5 for 4315, and the direction of variation is in harmony with the evidence furnished by sun-spot and by arc and spark data.

With the great multiplicity of fine lines, especially in the G and later types, we cannot be certain that lines which are apparently pure are not in reality affected by superimposed unknown components. Bearing this possibility in mind we may provisionally regard as pure such lines as 4468.6. For the pure lines we cannot at present predict the direction and approximate amount of variation of the wave-length with type, as can be done for the great majority of the blended lines, except as an unsymmetrical change of width in sun-spots may give an indication. For these "pure" lines the agreement between the two observers is also satisfactory for the material at hand. The observed differences for 4246.9 are too small to be regarded as discordances. The large discordance in the G type for 4260.6 seems clearly due to the inclusion by Voûte of rather widely distant companions to the violet. For 4274.96 somewhat large accidental variations may be involved in the moderate apparent discordance. For Hγ the agreement is good for types A, G, and K (F5 is discordant), and the direction of variation is that indicated by sun-spot data. As measured on the three-prism plates line 4399.9 is not pure, and this is probably true also of 4469.5. For 4468.6 the results are accordant. Although the wave-lengths are accordant for 4254.5 and 4359.8, with such small range not much can be expected in the way of confirming my variations with type.

SUMMARY

The stellar wave-lengths which Voûte determined recently were compared with those published by the writer in *Boletin No. 1* of the Córdoba Observatory, for the purpose of noting whether the former showed the same variations with spectral type as the latter.

Systematic corrections were applied to Voûte's wave-lengths purely to facilitate the comparison. The details for the comparison are contained in Table I. Bearing in mind that an appreciable range of accidental difference is to be expected for the data compared, Voûte's wave-lengths may be regarded as confirming my variations of wave-length with stellar type.

DUDLEY OBSERVATORY
ALBANY, N.Y.
December 1918

A PROPERTY OF THE PHOTOGRAPHIC PLATE ANALOGOUS TO THE PURKINJE EFFECT

SECOND NOTE

By J. A. PARKHURST

In the former note printed in the April number of this *Journal* (**49**, 202) the effect of star-color on the contrast of the photographic plate was investigated for the case of the ordinary plate, the results apparently confirming Abney's statement that the gradation of the plate increases as the wave-lengths of the light employed depart from that to which the plate is most sensitive. The amount of this increase for Seed 27 plates was found to be so slight that it is usually masked by the accidental errors.

The appearance of F. C. Jordan's important paper on "The Color-Changes of Certain Variable Stars of Short Period"[1] calls for this second note, since the question of the gradation of the plates is vital to his conclusions and is not explicitly treated in his paper. However, in Table II of his paper are given grating measurements of Pleiades stars on Seed 27 plates, which will yield evidence on this question when the stars are arranged according to color and magnitude. This evidence is shown in Table II*a* and II*b*, in which column 1 gives the designation of the stars in Bessel's notation, column 2 the B.D. number in zone $+23°$, column 3 the photo-visual magnitude and color-index, taken from Miss Parsons' tables in this *Journal* (**47**, 42, 1918), columns 4, 5, and 6 the difference between the square roots of the diameters (normal minus grating) and the mean value, for the three divisions of Jordan's table. Columns 7 and 8 give the mean values of these differences, grouped in Table II*a* according to magnitude, and in II*b* according to color-index.

The first table shows no appreciable systematic error depending on magnitude, if we except the two naked-eye stars Bessel *f* and *h*. These two images are $38'$ from the optical axis (a distance greater

[1] *Astrophysical Journal*, **50**, 174, 1919.

than is customary to use for photometric purposes) and somewhat elongated, enough to explain the excessive values of Δ. The remaining small progression in the values of Δ, from −0.03

TABLE I*a*

EFFECT OF COLOR ON SCALE—CRAMER TRICHROMATIC PLATES, FILTER β 10
PLATE UV 504

STAR	SPECTRUM	$\frac{\Delta S}{8^m-1^m}$	MEANS		$\frac{\Delta(\Delta S)}{\Delta S}$
			Spectrum	ΔS	
17.....	A0	9.65			
+25°2498.....	A0	8.42			
21.....	A0	8.74			
16.....	A2	8.76			
12.....	A2	9.46			
13.....	A2	9.33	A3	8.62	
+26°2326.....	A4	7.75			
+26°2329.....	A4	6.61			
+26°2343.....	A4	7.51			
14.....	A5	8.81			2 per cent
+26°2345.....	A6	8.28			
18.....	Fp	8.09			
+24°2455.....	G	9.48	G	8.78	
+27°2114.....	G0	8.97			
15.....	K5	8.60			

TABLE I*b*

PLATE UV 1153

STAR	SPECTRUM	$\frac{\Delta S}{g-f}$	MEANS		$\frac{\Delta(\Delta S)}{\Delta S}$
			Spectrum	ΔS	
17.....	A0	6.70			
21.....	A0	6.31			
12.....	A2	7.65			
13.....	A2	6.41	A2	6.86	
16.....	A2	6.64			
+26°2329.....	A4	7.4			
14.....	A5	6.93			5 per cent
18.....	Fp	7.18			
+27°2114.....	G0	7.76	G2	7.20	
7.....	G5	6.6			
15.....	K5	7.30			

to +0.01, is 2.6 per cent of the quantity measured and might indicate a slight error in the square-root formula used by Jordan.

The second table (II*b*), in which the stars are grouped according to color, also shows a slight difference in the gradation of the plate between the group of sixteen stars having a mean color-index of +0.01 (therefore white stars) and the group of four stars having a mean color-index of +0.33. The difference in gradation between

TABLE II*a*

EFFECT OF COLOR ON SCALE—SEED 27 PLATES, NO FILTER
ARRANGED IN ORDER OF MAGNITUDE

DESIGNATION		MAG. *P-V*	Δ_1	Δ_2	Δ_3	MEANS	
Bessel	B.D					Mag.	Δ
f	557	3.73	+0.12			4.44	+0.18
h	558	5.15	+0.24				
p	536	6.24	+0.03	−0.14		6.68	−0.03
s	556	6.56	−0.04	−0.11			
32	561	6.66	+0.07	+0.09			
24	540	6.93	−0.02	+0.06			
29	553	6.99	−0.05	−0.04			
19	537	7.04	+0.01	−0.05		7.39	−0.02
17	535	7.07	−0.08	−0.07			
4	512	7.18			−0.21		
22	538	7.19	−0.17	−0.05			
31	560	7.54	+0.26	+0.03			
23	539	7.81	−0.04	+0.25			
7	517	7.87			−0.02		
33	562	8.01	+0.11	−0.06		8.30	+0.01
1	510	8.06			+0.02		
18	534	8.27	−0.21	+0.09			
27	549	8.31	+0.12	+0.02			
13	528	8.46	−0.09	+0.03			
15	531	8.68	+0.04				

these two groups, 0.04 = 2.6 per cent of the range measured, is in the direction opposite to that shown by the Coma stars in the former paper, but, being within the accidental errors of the plate, cannot be considered of much significance. The conclusion therefore seems justified that for ordinary plates the gradation is not appreciably affected by star-color.

The effect on the photo-visual scale remains to be considered, for the color-sensitive plate used behind a yellow filter is only

affected by the rays of wave-lengths near the yellow, whereas the plates themselves are fully twice as sensitive to the blue rays. A priori reasoning from the behavior of the ordinary plate would seem useless in this case; therefore the plates themselves must yield the evidence. Jordan states near the foot of Table II that "trichromatic plates and filter were also tested with the grating," but he gives no details. Presumably these were also plates of the Pleiades,

TABLE II*b*

ARRANGED IN ORDER OF COLOR-INDEX

DESIGNATION		COLOR-INDEX	Δ_1	Δ_2	Δ_3	MEANS	
Bessel	B.D.					Color-Index	Δ
h	558	$-0^{M}19$	+0.24				
29	553	−0.17	−0.05	$-0^{M}04$			
f	557	−0.13	+0.12				
32	561	−0.12	+0.07	+0.09			
31	560	0.00	+0.26	+0.03			
23	539	+0.01	−0.04	+0.25			
22	538	+0.02	−0.17	−0.05			
4	512	+0.04			$-0^{M}21$	$+0^{M}01$	$+0^{M}01$
33	562	+0.04	+0.11	−0.06			
13	528	+0.05	−0.09	+0.03			
19	537	+0.08	+0.61	−0.05			
7	517	+0.08			−0.02		
p	536	+0.09	+0.03	−0.14			
1	510	+0.09			+0.02		
24	540	+0.11	−0.02	+0.06			
18	534	+0.16	−0.21	+0.09			
27	549	+0.21	+0.12	+0.02			
15	531	+0.37	+0.04			+0.33	−0.03
s	556	+0.30	−0.04	−0.11			
17	535	+0.43	−0.08	−0.07			

with a small range of color, as is seen in Table II*b*, and therefore not so well adapted for the purpose as plates of the Coma group. However, two plates of the Coma group taken with the Zeiss ultra-violet camera are available. These were Cramer trichromatic plates taken behind filter β 10, the counterpart of filter β 7 used by Jordan on the 2-foot reflector, so that the results will be strictly comparable with those found by Jordan. The data obtained from measures of these two plates are given in Tables I*a*

and I*b*, where column 1 gives the Bayer or B.D. number of the star, column 2 the spectral class found from objective-prism plate OP 38, column 3 the difference in scale-reading between two exposures. In case of plate UV 504 the exposures were of different times, eight and one minutes respectively; on UV 1153 the free image (*f*) was compared with the central image (*g*) of an exposure through grating R 6. The measures in column 3 were made by comparing the focal images with an artificial scale formed by a series of images of a polar star taken with a constant time-ratio, $\sqrt{2}$. The means of spectral class and ΔS are given in columns 4 and 5 and the percentage of increase in column 6. As in the previous tables, these differences are taken in the sense that they increase with the gradation (contrast) of the plate; therefore with the trichromatic plate and filter, these two plates show a slightly greater contrast ($3\frac{1}{2}$ per cent) for the colored stars of spectral class G than for the white stars. This may be interpreted as following the same rule as the ordinary plate, the contrast being greater for the yellow light to which the combination of plate and filter is most sensitive, and less for the white light. In this case also the amount of the increase is of the same order as the accidental errors of the plate.

SUMMARY

1. The effect of star-color on the gradation (contrast) of the photographic plate is small, being of the same order as the accidental errors.

2. The direction of the change in gradation is found to agree with Abney's law that it should increase as the wave-length of the light employed departs from that to which the plate is most sensitive.

3. This is found to be true for the ordinary (Seed 27) plate, giving photographic magnitudes; and also for the combination of Cramer trichromatic plate and yellow filter, giving photo-visual magnitudes.

YERKES OBSERVATORY
July 1919

ON THE DIFFUSING ACTION OF THE SUN'S GASES AS THE CAUSE OF THE APPARENTLY SHARP SOLAR BOUNDARY

By C. G. ABBOT

I have recently received a pamphlet entitled *Etudes sur le Rayonnement Solaire* (*Extrait des Archives Neerlandaises des Sciences Exactes et Naturelles* (III A), **5**, 1, 116, 131, 1918). This pamphlet contains papers by J. Spijkerboer, W. H. Julius, and B. J. Van der Plaats. In the first of these papers Mr. Spijkerboer deals with my views as to the diffusing effect of the gases of the sun as the cause of the sharp boundary of it. It seems to me he has not carefully read my statements and so has overlooked some considerations which go to support my conclusions. As the matter is of great interest, I venture to explain my views somewhat further. Referring to page 109 he says:

Abbot aussi s'est occupé de l'évaluation de la profondeur des couches diffusantes du soleil, mais il arrive à une valeur qui me paraît trop petite.

Il dit que, d'après des mesures effectuées à Mount Wilson, il se perd par diffusion dans l'atmosphère terrestre 5 pour cent du rayonnement solaire pour la lumière jaune. A son avis une couche contenant 75 fois plus de gaz doit donc produire la perte par diffusion de 99 pour cent au moins du rayonnement. Or, cela est inexact.

A la page 50 (Tableau XVII) de notre travail il est dit qu'une couche pour laquelle H = 1/10 laisse passer, dans une direction perpendiculaire, 95 pour cent du rayonnement incident. Mais une couche pour laquelle H = 8, c. à d. 80 fois plus grand, laisse encore passer environ 17 pour cent du rayonnement incident. Pour trouver une couche qui ne donne que 1 pour cent du rayonnement et dans laquelle il se perdrait 99 pour cent par diffusion, H devrait être très grand.

La formule de Schuster

$$R_0 = \frac{2}{2+H} S$$

(voir p. 7 et se rappeler que $H = st$), qui peut être admise comme grossière approximation, nous donne aussi une idée suffisamment exacte de cette question.

Si nous admettons maintenant que la masse gazeuse doit être 10 fois plus grande que ne l'a calculé Abbot, nous ne pouvons pas dire, eu égard aux variations de pression et de température, que nous devons aussi aller à une profondeur dix fois plus grande, mais dans tous les cas il doit encore venir de la lumière de profondeurs beaucoup plus grandes que ne l'indique Abbot.

He has not noticed that my statement dealt only with the direct beam. I had stated: "If, as computed by Schuster, the quantity of gas in the vertical column of atmosphere above Mount Wilson is sufficient to scatter from the direct beam of yellow sunlight six per cent of its light, a column containing seventy-five times as much will suffice to scatter ninety-nine per cent."[1]

My result follows directly from the extinction formula of Bouguer and Lambert, whose accuracy is capable of experimental demonstration. It will be convenient to refer in this connection to a paper entitled "New Evidences of the Intensity of Solar Radiation Outside the Atmosphere," *Smithsonian Misc. Coll.*, **65**, No. 4, by Messrs. Abbot, Fowle, and Aldrich. Referring to page 7 of that publication, Mr. Fowle showed that the observed atmospheric transmission coefficients above Mount Wilson differ by very small amounts from those which would be found for dry air. Employing the values observed on clear days, with trifling corrections for humidity, Mr. Fowle has been able to compute, according to Lord Rayleigh's theory of diffusion, the number of molecules per cubic centimeter in air at standard temperature and pressure. He finds the value 2.70×10^{19}, agreeing almost identically with Millikan's value 2.705×10^{19}, which is obtained by wholly dissimilar laboratory methods.

This indicates that we may regard the results obtained on the transmission of light through the atmosphere above Mount Wilson on the clearest days as fairly representative of those which would be obtained in a gas free from dust, as we must suppose the gas of the sun to be.

Referring now to page 26 of our publication, we see that on September 20, 1914, Bouguer's formula for the atmospheric transmission represented all the observed intensities found by spectrobolometric analysis within an error of generally much less than 1 per cent. In other words, the direct transmission of a dust-free gas is equal to a constant which we call the transmission coefficient raised to a power proportional to the number of molecules of the gas traversed. This is confirmed by experiment through a range of path including twenty times as many molecules as are found in

[1] *The Sun*, Appleton, 1912, p. 244.

the vertical layer of atmosphere above Mount Wilson, and no doubt it holds for indefinitely thicker layers where monochromatic radiation is concerned.

As the 75th power of 94 per cent is somewhat less than 1 per cent, it seems that my statement quoted from *The Sun* is correct, and we may justly conclude that less than 1 per cent will remain in the *direct* beam of yellow light which traverses a path in the solar envelope which contains 75 times as many molecules as does our atmosphere vertically above Mount Wilson.

This statement is entirely harmonious with Mr. Spijkerboer's, for while the *direct* beam is thus practically cut off in traversing such a layer, yet that does not prevent the light scattered to and fro by molecules from reaching the boundary of the sun by a tortuous course from layers situated much deeper than that which is just indicated.

I would draw attention, however, in this connection to the fact that the formula of Schuster and statements of Spijkerboer are based upon the assumption of zero absorption for the gas which forms the path of the rays in question. As shown by Plate XVIII of my book *The Sun*, Dr. Gale has found that the effect of pressure is to broaden greatly the lines of emission of the spark spectrum of titanium, so that under a pressure of seventeen atmospheres in carbon dioxide gas the narrow lines are broadened out to be a continuous spectrum of quite considerable intensity. This being so, it must follow that gases under such pressures must be not only radiating but absorbing over a continuous spectrum. The pressures which exist in the outer solar envelopes are not well known, and perhaps cannot be determined accurately, but yet in view of the enormous gravitation of the sun and the large mass of gas which would be required to contain 75 times as many molecules as exist above Mount Wilson, one would be justified in supposing that at least toward the bottom of such a layer the pressure must be very considerable, and amounts no doubt to a great many atmospheres. Hence we may suppose that the absorption of such a gas all through the spectrum is by no means negligible. This is the more probable when we reflect that a great number of chemical elements, many of which have very numerous spectrum lines, are mixed together, so

that there is scarcely a wave-length of the solar spectrum not close to some line of powerful absorption by some of these elements. Hence the tendency is to reduce our estimate of the depth from which the rays may come both in the direct beam and tortuously by scattering. I am inclined to think, in view of this consideration, that possibly my estimate is after all not too small, even if it is taken for the limiting depth from which yellow rays can come to the surface by *any* path whatever.

However this may be, the point I wish to make and to emphasize is that a *direct* beam of yellow light traveling by a geometrical path as in a homogeneous medium (by which I mean a smooth curve and not a zigzag line of many elements) will be practically cut off in the sun within a distance which contains roughly 75 times[1] as many molecules of gas as our atmosphere above Mount Wilson, owing to the molecular scattering such as produces the prevailing blue of the sky.

As for radiation of other colors, the results vary rapidly with wave-length, as shown in the following table. This gives the coefficients of vertical atmospheric transmission above Mount Wilson for dry air, as determined by Fowle[2] from our spectrobolometric observations, and the corresponding exponents giving the proportionally increased number of molecules, compared to those of our atmosphere, required for a scattering of 99 per cent from the *direct* beam.

Wave-length in μ	0.350	0.397	0.452	0.503	0.598	0.686	0.812	0.987
Coefficient.....	.632	.752	.840	.885	.913	.959	.980	.987
Exponent.....	10	16	26	38	50	110	228	350

Both the result expressed in this table and the relative paucity of strong absorption lines toward longer wave-lengths tend to show the condition accepted by Spijkerboer, and dwelt upon in my book *The Sun*, and by Schwarzschild as quoted by Spijkerboer, namely, that the longer wave-lengths arise at lower levels in the

[1] Or better, 50 times, as stated in the next paragraph.

[2] See Table 6 of our publication above cited. I prefer these data to those used in the statements quoted from *The Sun*.

sun than the shorter ones. At the same time it is to be noted that the immense pressures which must soon be reached tend to increase rapidly both the absorption and the scattering, so that actual increase of linear depth with wave-length is by no means so rapid as would otherwise appear.

Let us now turn to the larger question, namely, the cause of the apparently sharp boundary of the solar disk. Mr. Spijkerboer says:[1]

> Les trois explications suivantes du bord solaire méritent notre attention.
>
> A. Qu'on se rappelle qu'une hauteur de 700 km sur le soleil correspond à 1″ d'arc. Si le pouvoir rayonnant diminue, au bord, d'une façon continue, il est vrai, mais si rapide qu'à une hauteur de 700 km au dessus d'une couche émettant de la lumière blanche il se trouve déjà une couche gazeuse ne donnant plus un spectre continu, on doit alors observer un bord net (Schwarzschild).
>
> B. La limite nette du soleil s'explique par la réfraction régulière des rayons, due au gradient de densité dans le sens radial (Schmidt).
>
> C. La courbure des rayons par des gradients de densité irréguliers est la cause de la netteté de la limite (Julius).
>
> Nous excluons immédiatement une quatrième explication de la netteté du bord du soleil, celle que donne Abbot et qui est uniquement basée sur la diffusion. Abbot, en effet, commet une erreur dans ses considérations: il ne fait attention qu'à la longueur des chemins a l'intérieur de la masse gazeuse diffusante et ne tient aucun compte des conditions de rayonnement dans lesquelles se trouvent les points des chemins parcourus, chose qui, dans une saine compréhension du problème de la diffusion, aurait dû etre considérée en premier lieu.

With regard to the summary and adverse manner with which Mr. Spijkerboer deals with my view of the cause of the sharp boundary of the sun, it seems to me he has singularly misunderstood my position. At the very outset I assumed exactly the same rapid decline of temperature and density to account for the rapid decline of luminosity toward the solar boundary as does Schwarzschild and also Emden. Not only scattering but also the effect of temperature is dwelt upon by me with particular emphasis. My view was stated in the following words:

> It will be assumed: *a*) The sun, excepting perhaps in sun-spots, is wholly gaseous or vaporous. Except in sun-spots the photosphere is too hot to contain solids or liquids. *b*) The density of the gases rapidly diminishes, and their temperature rapidly falls from within outward across the apparent boundary of the sun.

[1] *Op. cit.*, p. 98.

It seems probable that gaseous scattering alone prevents us from seeing toward the center of the sun, when looking directly at the middle of the solar disk, to more than 5,000 miles below the reversing layer.

At the limb of the sun, the direct line of sight to a position at the same distance radially below the reversing layer would traverse fully 60,000 miles of gas. Accordingly, to obtain our column containing the requisite quantity of gas for practical extinction of yellow light, at the limb we should penetrate a layer which, measured along the radius, would be very much thinner than that required at the center of the disk. For, even to a radial depth of only 500 miles, the direct line of sight is almost 20,000 miles.

These considerations seem to point to a reasonable explanation of the sharp boundary of the sun. For at the edge of the disk, owing to the oblique line of sight, gaseous scattering will probably extinguish almost all yellow light starting from more than 500 miles below the chromosphere, while an even less thickness suffices for blue or violet light. It is plain that an indistinctness of outline corresponding to a layer of this depth would not be readily recognized on the solar image, since it corresponds to only about one second of arc. Furthermore, the direct line of sight takes in not only the nearer, but the farther solar hemisphere as well. A still thinner stratum than 500 miles would, therefore, suffice to contribute all the light that can be contributed to the beam directly along the line of sight. We therefore conclude that within a small part of a second of arc below the reversing layer the sun would appear as a solid body, even though entirely gaseous.

. . . . . .

Importance of Temperature.—It will be noted that in the solar hypothesis we are recommending the temperature plays a most prominent part. . . . . The darkening toward the limb is regarded primarily as a temperature effect, secondarily due to scattering. Owing to scattering, the effective radiating layer must necessarily be nearer the surface, and hence cooler, at the limb than at the center of the disk. We say it must be nearer the surface: For, travelling obliquely, a ray must become extinguished by scattering in the gas at the limb, before it reaches the same radial depth that it does if travelling radially at the center. The darkening at the limb would naturally be greater for violet than for red rays, firstly, because with all incandescent bodies a fall of temperature causes more decrease of radiation for short rays than for long; and, secondly, because molecular scattering is greater for violet rays than for red, and hence at the sun's edge the effective radiating layer for the violet will be more near the surface than will that for the red.[1]

See also the following:[2]

Under solar conditions, contrasted with terrestrial ones, scattering takes place on rays arising from every direction instead of from one direction alone.

[1] *The Sun*, pp. 237 and 245.

[2] *Astrophysical Journal*, **44**, 39, 1916.

Accordingly the beam which seems to come from the center of the sun's disk, as (to use a homely illustration) the handle of an umbrella comes from its center, really comes largely by scattering from all sides, just as the strength of the umbrella handle arises from its ribs.

For brevity I have omitted the data which led me to the numerical values given. These the reader may consult in my book if he pleases. In the latter part of this quotation I speak repeatedly of "the direct beam." As I have said above, I do not at all deny that rays may come to the eye through an indirect zigzag course from points situated within the sun at greater distances than those indicated, but, as I have also said, the most certain existence of absorption in the solar gases tends to limit us even in this possibility, so that perhaps even the farthest depth of the medium from which the yellow rays come to us by any course whatever may not greatly exceed the depth which I have here assigned.

What seems clear, however, is this, that whatever objects might lie as a background within or behind our sun, their rays could not pass through the solar gases so as to yield any optical image of the supposed background when the path of these rays traverses a great depth below its exterior. For there would be found in the path abundantly sufficient molecules practically to extinguish all *direct* rays from the farther source. The sun up to within a few miles of its edge would then, on account of scattering alone, behave like a solid body as far as concerns interposing a perfect obstacle to the passage of the direct beams of light required to make optical images.

On account of the great diameter and spherical form of the sun the relative number of molecules found in a direct line of sight increases with extreme rapidity as the line of sight passes inward from the outer boundary of the sun. The absolute increase of the number of molecules depends of course upon the density of the gases at the region in question. The brilliance of the sun in this neighborhood depends both on the density of the gases (which influences the intensity of the emitted and scattered light) and on the temperature of the gases on which depends the intensity of the primary radiation. These are the considerations which led me to introduce the second assumption quoted above from my book *The Sun*, namely: "*b*) The density of the gases rapidly diminishes and

their temperature rapidly falls from within outward across the apparent boundary of the sun." This stipulation appears to have been overlooked by Mr. Spijkerboer in his statement to the effect that I had not considered the conditions of radiation at the limb of the sun.

When we consider the complexity of the conditions: (1) that the depth at which the rays we see arise depends on their wave-length as influencing both scattering and absorption; (2) that their intensity depends on the temperature and absorption of the gases through which they pass, as well as on the scattering by these gases, and (3) that the absorption and scattering depend upon the density, which itself is a function of the temperature of the gases, and (4) that the density depends upon radiation-pressure as well as on gravitation, it seems clear that it is almost futile to investigate theoretically the distribution of brightness over the sun's disk, as has been done by Mr. Spijkerboer and others, without first investigating by the aid of thermodynamics and otherwise the probable distribution of density and temperature toward the limb of the sun.

There is one condition which simplifies the matter, for it makes it unnecessary to investigate the density of the outermost regions of the solar gases. This is as follows:

We see the sun on a bright field of sky-light produced by scattering of the solar rays within our atmosphere. Even though the solar gases should continue with gradually diminishing density out to a vast distance beyond the apparent solar boundary, these appendages could not be seen wherever their combined scattered and emitted light is inferior to the light of the sky, except during total eclipses. The farthest visible limit to the sun must therefore be set where its combined diffused and radiated light equals in brightness the brightness of the sky. Hence we see a bigger sun during a total eclipse than ordinarily. This consideration removes from the problem the idea of very far-reaching, gradually fading extensions of the sun's brightness such as the proposition of a purely gaseous sun brings up to some minds. According to spectrobolometric measurements made at Washington,[1] May 14, 1907, the brightness of the sky outside the sun's limb was as follows. The

[1] *Annals Smithsonian Astrophysical Observatory*, **2**, 22, 1908.

brightness at the sun's center in the wave-lengths given in each case is taken as unity.

Distance in solar radii from sun's center.....	1.005	1.010	1.015	1.020	1.025	1.030	1.035	1.040
Brightness { Wave-length 0.46 μ..	.033	.015	.007	.004	.002	.001	.000	.000
Brightness { Wave-length 1.03 μ..	.058	.024	.013	.010	.007	.005	.004	.003

It is not claimed that these results are of great accuracy. They were obtained at a station where there is considerable humidity and dust which varies from moment to moment, so that the two series of measurements may not be strictly comparable. Besides this, optical and instrumental sources of error tend to make the brightness observed somewhat too large. However, they indicate that the sky's light close to the sun's disk is probably very much brighter than the inner solar corona at corresponding points, as it was observed bolometrically at Flint Island January 3, 1908, as follows.[1] The brightness at the sun's center is taken as unity.

Distance in solar radii from sun's center..	1.10	1.25	1.75
Brightness.....	0.0000013	0.0000004	0.0000000

Unfortunately the two series do not quite overlap, but it is well known from photography of the solar corona and chromosphere at total eclipses that the growth of brightness toward the sun's limb would leave the inner coronal brightness, within the range of positions above stated, far short of the sky brightness as observed at Washington.

Having cut off from consideration the region beyond 1.01 apparent solar diameters, our problem is to explain why the sun brightens, with sudden rapidity, certainly more than tenfold, and probably more than one hundred fold, from about 1.01 to 0.99 solar radius.

The gases of the outer layers of the sun are light-giving because at high temperature. Suppose, however, for the moment that this were not the case, and that like the terrestrial atmosphere they were

[1] *Ibid.*, **3**, 5, 1913.

too cool to radiate visible rays. How bright would the sun's envelope then appear? Without attempting any accurate reply to this question, we may at least partially fix our ideas regarding it by considering the observed brightness of the terrestrial atmosphere under the clearest conditions. As already stated, observations indicate that, at clearest, our atmosphere may be regarded as a purely gaseous scattering medium.

Referring to Table 50 (*Annals Smithsonian Astrophysical Observatory*, **3**, 145, 1913), neglecting the very bright region of sky close to the sun, the average intrinsic brightness of the whole hemisphere of the sky, measured for all wave-lengths combined in terms of that of the sun as unity and observed from Mount Whitney, California (altitude 4400 meters), on an exceptionally clear day was 0.0000015. The corresponding figure for Mount Wilson (altitude 1700 meters) on a day not so clear[1] was 0.0000035. Taking into account that (1) the average intensity of the rays shining on the air was somewhat reduced by preliminary scattering in the higher atmosphere; (2) the mass of air producing scattering above Mount Whitney is less than that above Mount Wilson; (3) the average mass of air involved (on account of obliquity) is to be regarded as perhaps twice as great as that corresponding to zenith sun; (4) according to Rayleigh's theory scattering is as effective backward as forward; we may on the whole set the average intensity of radiation of scattering corresponding to a layer of gas equal to that of the vertical thickness of our atmosphere above Mount Wilson, for hemispherical illumination, at 0.000001 times the intensity of the incident beam.

We view the sun as 0.00001 of a hemisphere. The gases close to the sun would receive its rays over nearly a full hemisphere. Accordingly we conclude that on the basis of the preceding figures a layer of solar gas containing as many molecules as the terrestrial atmosphere vertically above Mount Wilson would appear one-tenth as bright as does the sun owing to the scattering alone.

The brightness of the scattered ray increases with the thickness of the scattering gas, but not so rapidly. Thus from the original observations at Mount Wilson September 22, 1913, which yielded

[1] *Astronomical Journal*, **28**, 133, 1914.

one of the results quoted above, I find that for a solar altitude of 46° the sky brightness in the sun's azimuth was as follows:

Altitude	2°47′	7°18′	15°56′	26°5′	36°46′	57°15′
Air mass	15.5	7.4	3.6	2.3	1.7	1.2
Observed brightness $\frac{\text{sky}}{\text{sun}} \times 10^8$	860	790	660	630	880	650
$\frac{1}{2}\{1+\cos^2(\phi-46°)\}$ (See Rayleigh's theory)	0.76	0.80	0.82	0.94	0.98	0.98
Corrected brightness ratio (Line 3 ÷ line 4)	1130	990	800	670	900	660

In the last line of the table I take account of the fact that the scattering in any direction is governed by the angle which the scattered ray makes with the incident light. By this allowance I take away the influence of the angular distance of the sun from the point of observation, so that in the final line we see the variation of scattering as influenced merely by the variation of air mass indicated in line 2. As Rayleigh[1] states that the expression in line 4 is not applicable close to the direction of the incident beam, it is probable that the two last values are too high on that account.[2] The march of the values shows that the intensity of the scattered beam increases fairly slowly compared to the increase of number of scattering molecules. I do not know whether this would be so along directions nearly in line with the incident beam.

The numerical results given show that a layer of gas containing as many molecules as our atmosphere does vertically above Mount Wilson would probably scatter to the earth light of one-tenth the intensity of the sun, and that a great increase of the number of molecules in the path of the ray observed might strengthen the scattered light at least several fold. Thus neglecting radiation altogether (though in my view it is not a factor to be neglected) the scattering alone is sufficient to give illumination comparable to that which is found at the solar boundary, assuming there a very moderate thickness of solar gases at densities comparable

[1] *Phil. Mag.*, **41**, 1871.

[2] Professor R. W. Wood has lately shown me unpublished experimental results which indicate that the great brightness near the direct solar beam is due to motes of dust which produce intense diffraction of the ordinary sort.

with those in our atmosphere. The question that now remains is, How does the density of the solar gases increase as we go toward the center of the sun?

Referring to the work of R. Emden,[1] he states that the laws of thermodynamics, like the Newtonian gravitational laws, have no creative capacity. Just as little as on the ground of the gravitational laws our planetary system may be built up, even if one knows the masses of the central body and the eight planets, just so little can the relations of temperature and pressure on the sun be determined merely by the aid of thermodynamics, even though we have a correct knowledge of the values of the radius and the mass. For it is shown by the theory that for a given radius and given mass there may exist innumerable different solar organizations, each of which would remain in gravitational equilibrium. Thus it is quite impossible, according to Emden, to fix the distribution of density and temperature by merely theoretical considerations based upon the known mass and radius of the sun. His study of the matter does not at all limit him in the consideration of the probable rate of change of density and the temperature near the solar boundary. In his opinion[2] there is a layer some hundreds of kilometers thick near the boundary of the sun for which the density and pressure diminish so very rapidly that at a great distance from the sun, such as that of the earth, the 725 kilometers which correspond to an angle of 1″ of arc may diminish in brightness so rapidly as to give the illusory though apparent impression of a sharp boundary of the sun.

This condition, which Emden finds theoretically possible and which he regards as probable, is all that is required to meet my views of the sun's sharp boundary. I have shown that a layer of gas containing a moderate number of molecules is sufficient to cut off the direct beam coming from the regions which lie beyond. The same layer of gas is competent to scatter to the eye rays of nearly the same order of intensity as are found at the border of the sun's disk. It appears from the work of Emden that it is quite within the bounds of theoretical possibility that the increase of density

[1] *Gaskugeln: Anwendungen der mechanischen Wärmetheorie*, p. 404, 1907.

[2] Page 398.

as one goes inward along the solar radius may be sudden and rapid enough to meet the requirements of this view.

SUMMARY

Owing to molecular scattering and true absorption by its gases, radiation cannot travel more than perhaps 7000 kilometers in those outer layers of the sun which lie immediately beneath the chromosphere. Outside of the chromosphere the gaseous density is so small that neither by radiation nor scattering is the brightness comparable with that of our atmosphere near the sun. Parts below a depth of 7000 kilometers furnish us no rays at all but merely keep outer parts hot. Hence, so far as it is a source of radiation to the earth, the sun is like a hollow shell. This shell is thicker for longer waves than for shorter ones. It is also thicker at the center of the solar disk than at the limb. For, owing to obliquity of the line of sight, the rays traversing 7000 kilometers lie near the surface at the limb, and are there probably confined within a layer less than 1″ of arc, or 725 kilometers thick. Hence the solar disk appears sharp, for an indefiniteness of 1″ of arc is not distinguishable from effects of bad seeing. Terrestrial examples of gaseous scattering show that the rapid increase of brightness at the solar limb is well accounted for if only the increase of density there is as rapid as was supposed by Emden and Schwarzschild. Readers are referred to the preceding article for support of these statements.

SMITHSONIAN ASTROPHYSICAL OBSERVATORY
WASHINGTON, D.C.
September 1919

Minor Contributions and Notes

THE GENERAL ILLUMINATION OF THE SKY

In his recent interesting article, published in the May number of this *Journal* (**49**, 266), Mr. V. M. Slipher has shown by irrefutable photographic observations that the green ray of the aurora is permanently present in the light of the sky. In consequence, Mr. Slipher questions whether the light of the aurora does not contribute an appreciable part in the total light of the heavens, which has been measured visually and photographically by different observers.

As to my own photographic measurements,[1] it seems to be certain that the ray at λ 5578 could not have had an appreciable effect on the result, for the following reasons: (1) The plates employed had an extremely slight sensibility to the radiation λ 5578. If that ray had been able to affect the plates appreciably, the visual observation would have given a brightness much more intense than that which was observed. (2) The photographic measures give very constant results, both from one day to another and in different years. Our measures were made in 1909. New determinations were made in 1917 by Mr. H. Bourget,[2] who employed the same method, and his results are almost identical with mine.

As to the visual method, Mr. Slipher lays stress on the discordance between my photographic determinations and the visual measures of Mr. Yntema;[3] but, per contra, the measures of Newcomb and those of Burns are in very good agreement with the photographic measures and completely exclude the possibility that any considerable proportion of the light is due to the so-called

[1] *Astrophysical Journal*, **31**, 394, 1910.

[2] *Comptes Rendus*, **166**, 943, 1918.

[3] For bibliography see Mr. Slipher's article, this *Journal*, **49**, 266, 1919.

green radiation. I am not in a position to give an explanation of the anomalous result found by Yntema. I will only remark that a variation in brightness of from 1 to 4 appears improbable; a brightness four times greater than normal would make the Milky Way almost invisible.

Visual measures on sources of illumination more faint than those of the sky[1] should be very difficult, while the photographic measures are easy and certain. If the visual measures are regarded as useful, it would be better to make them by the photo-visual method, with the use of an orthochromatic plate and a filter.

There are several problems which remain to be solved on the subject of the general luminosity of the sky. In particular there are no reliable observations available which permit us to say whether or not there is a variation, either photographic or visual, related to the solar periodicity. Also, may we not approve of Mr. Slipher's proposition for co-operation in studying this important question? Valuable results probably can be reached with instruments that are inexpensive and with a moderate amount of work. I venture to suggest the following scheme for co-operation in such researches.

1. A small number of regions of the sky, perhaps a dozen, having been selected, the intrinsic brightness should be measured photographically at several observatories (three or four, for example) at fixed dates and fixed hours. We should thus see whether the place, the date in the year, the time of day, or the solar activity had any effect on the luminosity of the sky. It would be well to choose regions of the sky among those which had been studied in respect to the density of the stars.[2]

A single observer in each one of the observatories, devoting one evening a week to these researches, would probably be all that was necessary. The plates could be measured with the microphotometer in a single laboratory.

2. Certain photo-visual measures could be utilized; they would yield the color-index of the general light of the sky.

[1] This brightness is almost that of a perfectly white surface *illuminated* by a candle placed at 70 meters.

[2] By my photographic method it would be necessary to make the measurement on a circle at least 1° in diameter.

3. It would be useful to make observations of the green radiation, not only in a qualitative way, but also in measuring its intrinsic brightness. Mr. Slipher's observations show that the "green" radiation is present even when the aurora is not visible. There is no proof that this diurnal illumination follows the variation of the solar activity, or even that it may be due to the same cause as the aurora (cathode rays emitted by the sun).

For the study of the first two questions, the methods are completely established and may be employed almost without experimentation; but for the third question certain preliminary researches would be necessary. A necessary condition for the fruitful study of the luminosity of the sky is that the situations should be far from large cities. Unfortunately most of the European observatories do not at all fulfil this condition.[1]

CHARLES FABRY

FACULTÉ DES SCIENCES, MARSEILLE
September 18, 1919

[1] The observations by Mr. H. Bourget, as well as mine, were made in the country during a vacation.

ERRATA

Vol. **48,** July 1918, "On Some Phenomena Observed in the Foucault Test," by S. Banerji:

Page 55, sixth equation, *for* $\frac{t}{T}$ *read* $\frac{t}{\tau}$, and similarly in the next line.

Page 56, fifth line, *for K read k;* also in the fourteenth line.

Page 57, the fourth term of expression (II) should read,

$$\frac{c_1}{2C_1k}\left[\sin k(A_1+B_1s+C_1s^2-\phi\xi_1)\cdot s\right]_{-s}^{s}$$

Vol. **48,** December 1918, "Change in Brightness, Spectrum, and Temperature of Nova Aquilae No. 3," by M. Maggini:

Page 309, in the fifteenth and sixteenth lines, *for* = *read* −.

Vol. **48,** December 1918, "The Period of V Tucanae," by B. H. Dawson:

Page 312, fourth column of Table II, last line, *for* +40* *read* −40*.

Page 315, fourth line from foot, *for* T−21415^d.427 *read* T−2421415^d.427.

Vol. **48,** December 1918, "The Radial Velocities of 119 Stars," by Joseph Lunt:

Page 263, footnote to Table I, *for* 229 *read* 299.

Page 265, second remark, *for e read a.*

Page 266, Table III, heading, *for* Cape (3) *read* Cape (2). Table III, fourth star, *for* † *read* ††. γ Aquilae, remarks apply to star 304 not 311.

Page 267, last line of table, *for* +0.09 *read* +0.08.

Page 270, Table IV, last column, for star No. 194 place a ¶ sign.

Page 271, first footnote, *for* plates *read* parts.

Page 273, Table V, last two lines, *for* †† *read* †.

Page 276, Table VI, *for* Leoporis *read* Leporis. For star No. 100, *for* * *read* †. Footnote, *for* Hα *read* Hγ.

Vol. **50,** September 1919, "Review of Recent Work on the Series Spectra of Helium and Hydrogen," by F. A. Saunders:

Page 155, in the second column headed "Formula," *for* $\frac{1}{2^2}, \frac{1}{3^2}, \frac{1}{4^2}$ *read* respectively $\frac{1}{1^2}, \frac{1}{2^2}, \frac{1}{3^2}$.

GENERAL INDEX
TO THE *ASTROPHYSICAL JOURNAL*, VOLS. XXVI TO L

(July 1907 to December 1919)

The *General Index* by authors and by subjects to Vols. I–XXV of the *Astrophysical Journal* (January 1895–June 1907), compiled by Professor Storrs B. Barrett, of the Yerkes Observatory, was issued in 1908. It made a volume of 133 pages, of the same size and style as the *Astrophysical Journal* itself.

Preparations have now been completed for issuing a similar index, to cover the twenty-five volumes concluding with the December number of the present year, 1919. Professor Barrett also will undertake the preparation of this index.

The price of the volume, in paper covers, has been set, for subscriptions in advance, at $2.50, postage prepaid. The edition will be limited and a much smaller number will be printed than in case of the prior index. It will be of much assistance to the publishers, in determining the size of the edition, to receive orders in advance. Subscriptions should be addressed to the University of Chicago Press, Chicago, Illinois.

It is hoped that the volume will be ready for publication early in 1920.

There are still on hand a considerable number of copies of the first *General Index*, which is sold separately at $1.50. Individual subscribers and libraries which have not heretofore acquired the first index will probably wish to purchase both. For those ordering both indexes in advance of the publication of the new index the price will be $3.25, prepaid. Communications should be addressed to the University of Chicago Press, 58th Street and Ellis Avenue, Chicago, Illinois.